FENDERS AND FENDER SYSTEMS: A STUDY OF DEVICES USED TO PROTECT BERTHING STRUCTURES AGAINST THE IMPACT OF SHIPS

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A STUDY OF DEVICES USED TO PROTECT

BERTHING STRUCTURES AGAINST THE IMPACT OF SHIPS

by

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Thesis
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SUMMARY

An investigation of the technical literature of waterfront structures for information on fenders impressed the author by the fact that only within the past decade has any serious note been taken by other than a few engineers of the importance of fendering. As late as 1944 the Engineering Index contained no reference to the subject of fenders, and when it finally did list articles on fenders there were no more than perhaps four or five in any one year, with most of these being of an elementary nature giving little information of a worth-while nature. Lately engineers and designers such as Minikin, Little, Robertson, and Baker (all Englishmen) have been publishing articles of great value on the subject. At least one company has been formed (Port and Harbour Fenders, Ltd.) that deals with the problem of design and construction of fenders. It is the author's opinion though that the basic facts pertaining to fender design are still not clearly known or presented, and that much work of a more highly theoretical nature has yet to be undertaken.

The design of fenders involves the use of energy equations in addition to those of statics. It is assumed by the engineers that energy of the lateral movement of the ship impinging on the pier or berthing structure is derived from the standard energy formula,

$$E_k = \frac{1}{2} MV^2.$$

It is customary to multiply this answer by a coefficient that in effect compensates for the energy losses of the hull of the ship, friction, yawing moments, and other losses. This coefficient is taken to equal

from 0.25 to 0.90 depending upon the type of ship, the arrangement of the pier, and many other intangible factors. The selection of such a coefficient is largely a matter of experience and cannot be set up as an empirical figure for each type of ship.

Any fender designed for a berthing facitily must be capable of taking the impact energy of the ship. The energy absorption of a fender is usually considered to be a function of the average force times the distance that the fender is deflected. This generalization is not true in all cases because the energy absorption rate changes in different materials and in the various types of devices. It should be remembered though that in dealing with the kinetic energy forces of vessels and the means of absorbing it, that the forces usually talked about are average forces and not maximum nor minimum. The average force for all intents and purposes is taken as one-half of the initial or maximum force.

Any fender or fending device or system is specifically used to absorb the kinetic or impact energy of the mooring vessels that have a component of velocity normal to the longitudinal axis of the berth. It is not considered necessary in most cases to absorb the impact of the longitudinal velocity components for these will either cause no damage or they will be checked by means of the mooring lines and bollards. Fenders may be utilized for purposes other than absorption of energy, but if so this is only a feature extra to the normal requirements.

Energy can be absorbed by bending, axial compression, axial tension, shear, or torsion, or any combination of the five depending

upon how the fender is arranged and designed. Each material will work best in one of these methods but will serve in any of them to a certain degree. Energy absorption by timber is usually considered to be best accomplished by bending, while in rubber compression is considered to be most economical. Rubber is better in compression for it will fail in shear or tension due to fatigue too rapidly. Springs are best in compression, but there is no reason why they cannot be used as effectively in tension or possibly in torsion.

Energy can also be absorbed by any material or device that requires that a force do work. In the case of the gravity fender, the elementary formula of work is used where the absorption is equal to a force times the vertical distance through which a weight or mass is raised. Caution is required here again for the force is also the average force. Hydraulic buffers or pneumatic fenders require the expenditure of energy to force the device to compress or move. In the hydraulic buffer, a fluid is forced to flow through a small, diminishing orifice at increasing velocity rates, while in pneumatic fenders air is compressed and/or forced through a small orifice.

Generally then, the design of fenders is a matter of equating energy equations to each other. On one hand is the available energy that must be absorbed, and on the other is the fender which because of its design characteristics must absorb the total kinetic energy that is impressed upon it. Contrary to the custom of many designers the analysis of the forces on fenders rarely includes static loads as the primary problem. It is highly recommended that all fenders be analyzed from

both a static and from a dynamic standpoint, for otherwise excessive stresses are very likely at high impact values. As an example, a timber fender pile may show that it is capable of taking all of the impact energy of a vessel, but if the analysis is carried to completion it may be found that the unit stress of the outer fibers is such that the member will fail in bending.

Fenders as standard devices on piers or quays used for berthing of large vessels are becoming more and more common and necessary. The larger the ships the more necessary are fenders as protection to both the ship and the berthing facility. At the present time a good deal of excellent work has been accomplished on the design and improvement of fenders, but there is much more that can be done to improve the current fendering methods and systems. The author has suggested several methods of new or different design, but he feels that even these are far from the ideal or perfect fender system. All marine and harbor designers are encouraged to consider this problem and to make an attempt toward developing an ideal system. Naval architects should be consulted regarding the effect of fenders on the hulls of the ships, methods of reducing the lateral velocity and energy of impact, and possibilities of modifying the basic design of ships to provide additional protection at those areas where the fenders will act.

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LIST OF SYMBOLS

A	cross-section area
C_1, C_2, C_3	arbitrary coefficients
c	distance from the centroid of a member to the outer fiber
D	depth of embedment of piling
D_f	depth of fixity of the pile
d	depth of water
d_o	depth of water where wave originated, or depth of deep water
d_p	diameter of pile
d_s	diameter of spring wire
E_a	capacity of a fender for absorbing energy
E_k	kinetic energy (usually referred to the energy of the ship)
E_p	potential energy
E_t	total energy
e_1	eccentricity of vertical load from center of pile
e_2	eccentricity of pile from plumbness; the amount the centerline of the pile deviates from a straight line
F	force of ship against a fender; wave force against a pile; etc.
F_a	average force (for a ship against a fender this will equal F/2)
G	modulus of elasticity in shear
g	acceleration of gravity (32.2 feet per second per second)
H	height of a wave
H_o	height of a deep water wave
I	moment of inertia
K_a	coefficient of active lateral earth pressure

K_p	coefficient of passive lateral earth pressure
L	length of wave
L_o	length of a deep water wave
ℓ	length of a pile
ℓ_a	height of the applied force on a pile above the ground line
M	mass of a ship (W/2g)
M_b	bending moment
m	mass of pier, wharf, quay, etc.
m_f	mass of fender or fender system
P	axial load
r_s	radius of a spring
T	period of a wave, seconds
V	velocity. feet per second, or inches per second
V_s	volume of a spring
W	displacement weight of a ship in long tons (2240 pounds); weight of a gravity fender
δ	total deflection of a fender or pier
γ_s	unit weight of soil, pounds per cubic foot
θ	angle between batter pile and the vertical
σ	unit stress, pounds per square inch
σ_a	maximum allowable unit working stress, pounds per square inch
σ_v	stress in shear, pounds per square inch.

I. INTRODUCTION

Since the time that man has built piers, wharves, and quays for mooring and unloading ships, he has been confronted with the problem of protecting both the ships and the waterfront structures from the forces of impact and lateral thrust during berthing operations or due to the action of storms on the moored vessels. Many different types of protective devices or fenders have been designed and used, but the majority of them are not acceptable, either economically or structurally.

What is a fender? In harbor engineering, a fender is a device, a structure, or a method which, by the absorption of kinetic energy, protects both the ship and the harbor structure from impact forces of the vessels. A fender or fender mechanism can take the form of a vertical pile, a block of rubber, a spring, a hydraulic buffer, or an old truck tire, all of which will absorb energy. At the present time a really efficient, effective fender or fender system has not been designed, although many attempts have been made. Many fenders in current use are fairly satisfactory, but none are ideal.

The importance of the fender to both the ship and the pier should not be overlooked. If a fender system is not available for berthing of the ship, extremely high unit stresses will be induced into the framing of the vessel thereby causing buckling of the plates and structural members. Not only are large forces applied to the ship, but the impact energy must be absorbed by the pier structure. Adding the effect of the impact to the lateral loads already carried by the

structure may, in cases of high mooring velocities of the ship, cause extensive local damage to the decking and piling of the pier.

Unfortunately, the use of fenders as energy absorbing media is still incompletely understood or appreciated by many engineers and designers of waterfront works. Because of this attitude large piers, wharves, and quay walls are being built that provide no adequate protection to either the ship or the structure. Many so-called fenders are so designed that they are completely ineffective because they require a sizeable deflection of the ships members before the fender can absorb the impact. It is believed that these designs are the outgrowth of an incomplete understanding of the action of fender systems and the requirements for energy absorption.

The author's purpose in presenting this thesis is to discuss thoroughly fender designs, present as many of the better or more frequently used systems as practicable, and to set forth ideas and possibilities for future development. An attempt is made to present herein many of the currently used methods of fendering, with analysis and discussion of each type. The author thinks that except for noting the obvious defects in particular systems no definite recommendations should be included so that the individual reader can come to his own conclusions depending upon the locality at which the fender is to be used. It is on this basis that the following thesis has been prepared.

The extensive use of mechanical fenders and fenders systems has been comparatively recent, following the advances of the development of the large modern steel ships. In the days of the wooden sailing

vessels and the wooden steam-driven ships fenders were crude and were not needed for much more than a minor absorption of impact energy, for the ship's hull itself was capable of absorbing the majority of the impact of berthing. In those cases where neither the ship, nor the pier or fender system was capable of withstanding the forces, then a ship's carpenter was employed to repair the damaged planking of the hull or a wharfbuilder to repair the piers.

As shipbuilders started to make use of iron and then steel for hull plates, and as they began to increase in size, weight, and speed of vessels, the problem of protecting both the ships and the piers at which they berthed became more and more of a problem. In sheltered, protected harbors where the berthing speed of ships can be rigidly controlled then the fender system is not too great a problem for here the engineer can install a more or less rigid system of wales and verticals that protect the main structure from abrasion only. A good many of the ports and harbors of the world fit into this category of being in a protected area, so that the need for a fender system to absorb large energies of impact is not required. It should be noted though that where large ships, in excess of 10,000 tons displacement, are concerned, rigid fendering can cause damage to the ship's structural members if the approach of the ship is not reduced to very low velocities. At the remainder of the ports though where sheltered conditions can not always be obtained and where the berthing of ships is such that the approach velocity normal to the pier exceeds about 0.2 feet per second, a fender system must be devised for protection of the

pier, or at least the main structure must be made considerably heavier to withstand the impact forces. You can not, though, increase the rigidity of the main structure to take the increased impact so that high unit stresses are created within the hull plates and framing of the vessel itself, or this will result in bending or possible failure of the plates or frames.

Here then is our problem: a method to absorb kinetic energy must be devised so that the stresses set up within the ship's members will be within safe limits, and so that the majority of the energy will be absorbed by a buffer system and not transferred into the main structure. The solution to the problem requires engineering reasoning. By comparing the anticipated velocities of the ship, the displacement tonnage of the ship, the mass of the pier, the potential life of the structural members, the possible lack of adequate maintenance, and the many other intrinsic factors the waterfront designer will be able to provide an acceptable fender system.

Given a specific size vessel, a standard approach normal velocity, and a relatively constant set of local conditions a fender system could be provided without much difficulty. In practice though it isn't that easy, for the design must be for the average. It must take into consideration the many different ways a vessel can strike the fenders, the shapes of the vessels, the accidental collision speeds of the ships at contact, hurricane wind forces, water currents, and the size of the ships. For instance, a fender that will be ideal for a ship of 30,000 tons would probably be very dangerous for use by a small

boat of 500 tons that has a high approach velocity. The rigidity of the system for the larger ship would be such as to damage the hull plates of the small boat because of high contact pressures.

In order to develop the requirements for the design of a fender system it is necessary to start with basic fundamental concepts of statics and dynamics, thereby establishing the underlying principles for the study. Primarily, a fender system is provided so that the kinetic energy of impact of the moving ship or floating mass can be absorbed before the vessel comes into contact with the main structure. Briefly then, a device is needed to absorb the impact of a floating object of any size approaching at any reasonable velocity, and to allow transmission of only a small portion of the energy, if any at all, to the main pier or wharf structure. Individual devices, the manifestations of the basic energy absorption concepts, will be discussed later in detail.

There are two types of impact that must be considered: the effect of kinetic energy forces on an individual fender, and the effect of a moving vessel on the over-all structure. The first is a concentrated load or impact that does not necessarily take into consideration the method of application nor the effect on adjacent fenders, while the second considers the method of application, the effect on the structure as a whole, and probabilities of reduction of the mass-velocity summation of the impact. From a consideration of these two effects, the designer can first develop a suitable fender for the various types of vessels that will be using the facility, and then by combining

these fenders into a system that will transmit the forces to the other members he can reduce the problem into its most simple components. Do not make the mistake of considering these two factors separately; both are dependent upon the other, provided an economical, efficient structure is to be realized.

Before consideration of the application of the various fender designs, it must be understood that the ships should have first consideration. They must be protected within reasonable limits. Of course, these limits cannot include poor ship handling, collisions, or disastrous weather conditions, but for all normal operations of the ships, they should be berthed without damage. Secondly, the pier or wharf must be protected from the blows of the ships. This feature will be discussed more thoroughly later. To accomplish these ends a device for absorbing kinetic energy must be designed so that it is not so strong as to damage the ship, but yet strong enough to prevent damage to the pier, and within reason should be able to withstand the applied stresses and weatherings with little repair or maintenance. Therefore it must be a mechanism that can absorb energy efficiently with no damage to the structures it protects and with no extensive damage or wear to itself.

In determining the design of a fender the following should be taken into consideration:

1. The kinetic energy of a ship approaching a pier should be absorbed completely, or as completely as possible, within a finite distance. The distance through which the energy is absorbed is dependent upon the mass of the vessel that will come to bear, its maximum velocity

of approach normal to the longitudinal axis of the pier, and the maximum force permissible on the hull of the ship.

2. The fender should be sensitive to the velocity of approach. In other words, the apparatus should be such that the rapidity with which the energy absorption takes place is directly proportional to the velocity of the impinging vessel. For a slow-moving ship, the fender should become effective slowly, but should give a resisting force of relatively large magnitude in comparison with the mass of the ship. For a rapidly moving ship, the fender system should build up a resistance from a relatively small quantity very rapidly to a maximum depending again upon the mass of the ship. In each case the energy imparted into the fender should be taken up through the full deflection of the mechanism, but in such a manner that there is little of no shock during initial contact of the ship, nor should there be any appreciable energy carried into the main structure after the fender has completed its deflection.

3. Insofar as possible the fender system should be sensitive to the mass of the impinging ship. The fending mechanism should not be of such magnitude that its weight approximates the weight of the vessel to be stopped. At this point consideration must be given to the needs of the larger as compared to the smaller vessels. A large gravity type fender because of the heavy weight characteristics that make it excellent for use with the larger ships, may cause excessive damage to smaller ships due to high unit stresses. Ideally, a fender that is mass sensitive will give large maximum forces for the larger

ships, and small maximum forces for the smaller vessels.

4. A fourth requirement of an idealized fender system is that the rate of energy absorption increases as the device deflects. In other words, the rate of absorption with respect to the distance travelled increases instead of being a linear function or constant. The rate would theoretically increase with the distance travelled by some power of δ greater than unity, or the force required to deflect the fender a distance $d\delta$ would be dF and the force required to deflect it twice $d\delta$ would be (2dF+k). Therefore, because the energy of the ship that is imparted to the fender reduces inversely as the square of the velocity, the fender system in order to maintain the same acting force theoretically can increase the energy absorption in an amount proportional to the square of the deflected distance.

At the present time the author knows of no fender system designed so that all of the above requirements will be met and there is some doubt if such is practicable. It is to be noted that it was not indicated that such a fender is not possible. Until different materials are devised or present ones modified, and until present maintenance procedures can be greatly improved, it is considered that a so-called perfect or ideal fender will not be available for use.

Referring to the fenders commonly used today, it will be found that the kinetic energy of impact is absorbed by one or more of the following methods:

1. Bending of structural members of timber, steel, and/or concrete
2. Deformation of fenders, bumpers, buffers, or isolators.
3. Absorption by causing flow of a fluid through orifices, or compression of volumes of air

4. Elastic and/or plastic deformation of the hull of the ship
5. Rolling and yawing of the vessels
6. Displacement of water between the vessel and the quay or wharf
7. Elastic deformation of the underlying soils
8. Energy required to overcome the inertia of the structure

As can be readily discerned, only 1., 2. and 3. above are directly applicable to fenders, while the remainder of the list is realized in any pier structure that comes into contact with a ship.

In the final analysis the selection of a fender design depends not only on the ships that will use it, the exposure of the site, the material employed, the design of the main structure, but also on economic maintenance considerations. Regardless of how well a fender device is designed and constructed, unless it requires little or no maintenance it will not be adequate to fill the requirements. A mechanism that requires constant maintenance will eventually become useless as the maintenance forces fail to properly care for it.

II. ANALYTICAL APPROACH TO DESIGN

A. General Energy Absorption Theory

There are certain basic concepts to be considered in the design of any fender, regardless of the composition or the material to be used. It is generally accepted that the computation of the kinetic energy of the ship that must be absorbed is derived from the formula, $E_k = \frac{1}{2} MV^2$. The absorbing quality of the deflecting fender is equated to the energy of the ship, and is in the form of $F \delta^x$. For a fender to be effective, the following equation must be satisfied:

$$\frac{1}{2} MV^2 = C_1 F \delta^x$$

where C_1 is an arbitrary constant referring to the number of fenders or devices that are acting to absorb the energy of the ship, and x is dependent upon the characteristics of the individual mechanism and is equal to or slightly greater than unity. After the fender system has been designed, the equation

$$\text{Efficiency} = \frac{\frac{1}{2} MV^2}{C_1 F \delta^x}$$

can be formulated giving the efficiency of a system, where the denominator is the actual absorption capacity of the fender. If the efficiency is unity the fender is presumably correctly designed. When the efficiency is less than unity, the system is still safe from the standpoint of the fender and the pier, but if the differential is large then damage will be sustained by the hull of the ship. When the efficiency is greater than unity, it is indicative that there will be a residue of

energy after the full deflection of the fender, and this remaining energy must be absorbed by the main structure itself. It is desired to provide a fender system so that the efficiency is as nearly unity as possible.

B. Forces Exerted by Ships

The energy of impact originates with the moving ship either during berthing or when moored and acted upon by waves, winds, or currents. It is usual to assume that the forces created by the berthing ship to be the greater and design on that basis, except in certain locations where the reverse is true. Therefore the energy of impact is taken as

$$E_k = \frac{1}{2} MV^2 = \frac{1}{2} \frac{WV^2}{g} = \frac{\text{Displacement, tons} \times (\text{Vel., ft/sec})^2 \times 12}{64.4 \text{ ft/sec}^2}$$

with the answer in inch-tons. In considering the tonnage of a ship, it is customary to use the long ton, or 2,240 pounds. Although all harbor engineers agree that the full kinetic energy of the approaching vessel is not mobilized against the fender, there is considerable divergence of opinion as to the exact amount of energy imparted by the ship to the pier. For purposes of example the value of 0.4 E_k will be used by the author throughout this paper. It cannot be too strongly stressed though that the use of 0.4 or any other coefficient should not be arbitrarily assumed as correct. Prior to design, an analysis of the site is the only way of adequately determining the correct value. For large ships values of 0.25 to 0.6 have been used extensively, while for the smaller, faster ships of 2500 tons or less values as high as 0.85 to 0.9 have been used. These higher values for the smaller vessels

reflect the construction of the ships as being of the "belted" types, which are round bottom and of slight draft so that little energy absorption is possible by the surrounding water.(40)* Kinetic energies of approach of different size ships at varying velocities normal to the line of the pier are shown in Figure 1. Note that the nominal energies of approach are used in conformance with the 0.4 coefficient.

If varying velocities of approach are assumed for different size vessels, it can be seen that the energy imparted to the fenders or main structure will be a relatively constant value regardless of the size of the ship. This will hold true of course only within a certain range of values, for as the ships get larger or smaller than the medium then the values must of necessity be modified. The smaller type of vessels will be light enough that usually damage will not result from impact, and in the case of a larger ship, the pier will usually be specifically designed for them. In most cases though, the engineer will be confronted with the problem of designing a structure that must provide impact absorption for a varying class of vessels within fairly definite limits. The design will be selected by taking into consideration the size and velocity of the ship. The average energy of impact for vessels can be usually taken as 400 inch-tons, while the figure of 1200 inch-tons is taken as the "accident" impact energy.(39) In any structure where moving loads and impacts are encountered there will be a certain possibility that through carelessness on the part of the ship handler, bad weather conditions, damage to the

* Numbers in parentheses within the text refer to the correspondingly numbered references in the Bibliography.

Velocity, ft/sec	Displacement of Ship, in tons					
	30,000	20,000	10,000	5000	2500	1000
0.4	358	238	119	59	30	12
0.8	1430	952	476	238	120	48
1.2	3220	2145	1072	536	267	107
1.6	5710	3810	1907	954	476	191
2.0	8940	5950	2980	1490	745	298

Figure 1 -- Velocity, Mass, Kinetic Energy of Various Types of Ships in Inch-tons

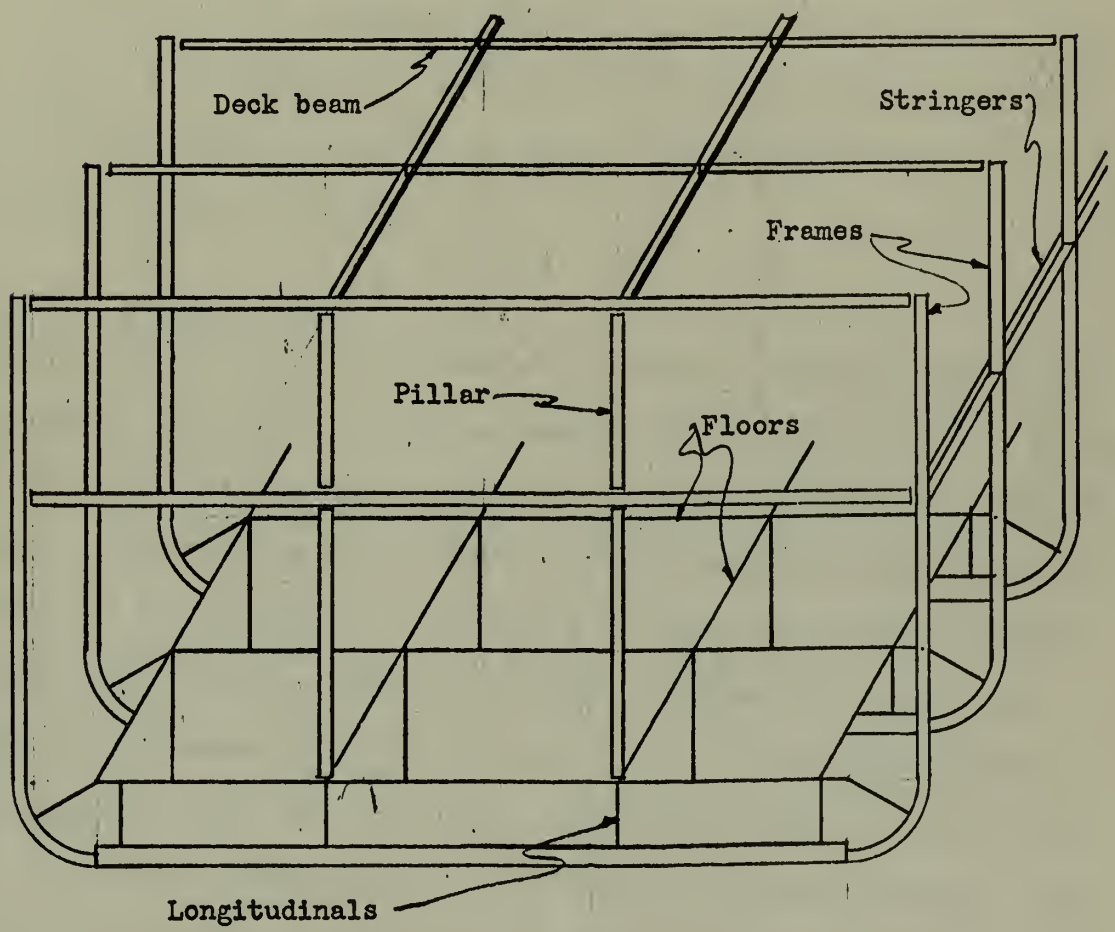


Figure 2 -- Transverse framing system of a ship

ship, or any other accidental source the ship may strike the pier at a velocity or angle such that the energy imparted to the individual fender exceeds that which it is capable of resisting. The limit of fender capacity is known as the "accident "energy. It is considered feasible to so design the fender and the main structure so that if the velocity of the ship exceeds the accident energy the ship will be the recipient of damage. It is impracticable to so design the main structure that it will collapse rather than damage a ship.

When selecting the design to be used for the fender system and determining how it will be positioned, the ability of the hull of the ship to take forces cannot be overlooked. The energy absorption of a fender is generally assumed to be

$$E_a = F \times \delta x$$

so that if the distance available for absorbing energy or deflection is decreased, the force, F, must necessarily increase if the fender absorption capacity is to remain constant. It can be seen then that both the force and the deflection are inversely proportional to each other. The force, F, is transmitted to the fender directly from the hull plates of the ship. Figure 2 shows the schematic section of a ship using transverse framing, and Figure 3 depicts a vessel using longitudinal framing.(6). With the force applied as a point load to the center of the span of the plate it can be seen that an excessive load will cause plastic deformation, and possible rupture in rare cases, of the plating, or when applied over a frame can cause plastic deformation to the structural member.

This structural deformation of the ship's hull and members, if it is kept in the elastic range, is one of the important energy absorbing factors to consider when dealing with fenders. In addition to the ship's deformation there is the resistance of the surrounding water to the motion of the ship in all directions of movement. The ship is not approaching the pier directly, but only with a component of its longitudinal velocity, and usually slightly bow on so that a yawing or turning moment is set up. As indicated in Figure 4 as the bow or forward portion of the ship comes into contact with the pier or fender system, the center of mass acting through a lever arm of distance. x, produces a couple that tends to swing the stern of the ship toward the pier and the bow of the ship away from the pier. The energy of moment is greatly absorbed by the turning moment and by the drag of the water thereby relieving the impact on the fender system. It is only the initial contact that imparts large energy forces to the structure. For the amount of energy that must be absorbed at first impact, Minikin uses the equation

$$E_a = \frac{C_1 W}{2g} (V \sin a)^2 + C_2 \frac{W}{2g} (V \cos a)^2$$

where C_1 and C_2 are coefficients each being less than unity, see Figure 5. The author feels that the second term of the equation is insufficient in that it assumes transmittal of the longitudinal component of velocity forces into the pier, whereas if the fender is adequately designed to compensate for frictional forces by providing a rotating surface to the fender, then this quantity can be all but

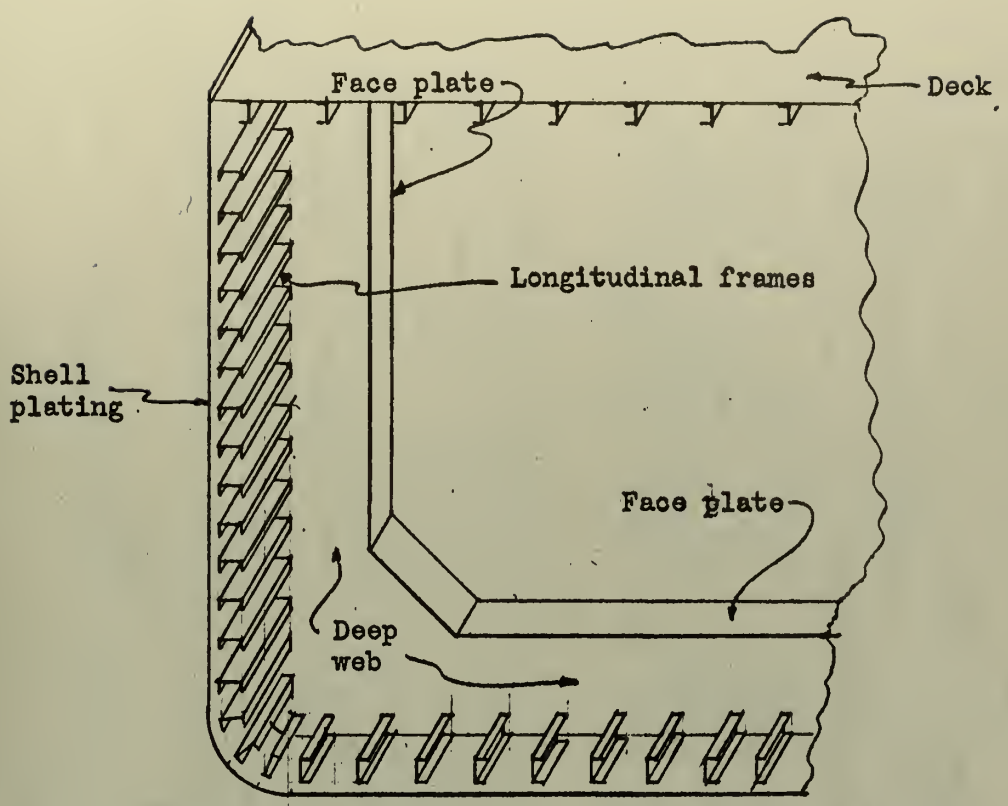


Figure 3 -- Longitudinal framing system of a ship

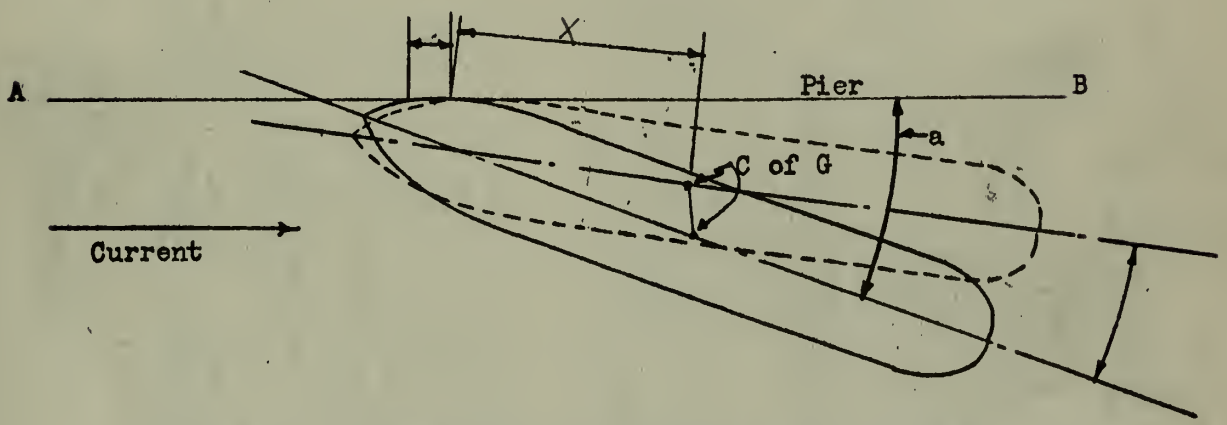


Figure 4 -- Turning moment of a ship striking a pier

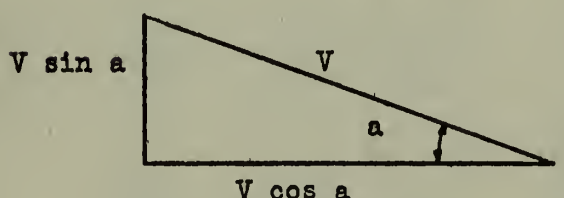


Figure 5 -- Vector diagram of ship velocities

Table I.

SUMMARY OF MAXIMUM TOTAL WIND AND CURRENT FORCES AND MOMENTS FOR VARIOUS CLASSES OF NAVAL VESSELS[‡]

A. Wind:

Type of Vessel[x]	Type of Mooring	Air Speed in knots	Maximum lateral force in tons	Angle of yaw in degrees	Maximum yawing moment in ton-ft.	Angle of yaw in degrees	Maximum longitudinal force in tons	Angle of yaw in degrees
Destroyer 376' x 41'	Pier Mooring	100	138	90	6152	50	20	150
Cargo 441' x 57'	Pier Mooring	100	244	90	5340	50	23	180
Carrier 499' x 65'	Pier Mooring	100	250	100	20,000	40	31	160

B. Current

Type of vessel[⊠]	2 knots			4 knots			6 knots		
	Maximum lateral force in tons	Maximum longitudinal force in tons	Maximum yawing moment in ton-ft.	Maximum lateral force in tons	Maximum longitudinal force in tons	Maximum yawing moment in ton-ft.	Maximum lateral force in tons	Maximum longitudinal force in tons	Maximum yawing moment in ton-ft.
Destroyer, 10.6' draft	(1)30	2.1	1050	116	6.2	3500	310	13.0	8200
Cargo, 7.5 Av. draft	(1)46	2.0	3200	120	5.0	7500	470	9.7	20,000
Carrier, 16.7 Av. draft	(2)65	2.6	1750	310	6.8	8200	1100	15.3	31,500

(1) 25 ft. depth of water. (2) 30 ft. depth of water.

⊠ Forces and moments are for single ships.
‡ After Ayers and Stokes, Reference 3.

ignored. Even if the fender is not designed to permit it to rotate, then there should be a factor in the velocity component that takes into consideration the coefficient of friction, thereby reducing materially the forces that are imparted to the main structure. The writer prefers to use an equation similar to

$$E_a = C_1 \frac{W}{2g} (V \sin a)^2 + C_2 \frac{W}{2g} (V C_3 \cos a)^2$$

where C_3 is a coefficient directly proportional to the coefficient of sliding or rolling friction, and can be modified from experience, taking into consideration the configuration of the side of the ship, oil slicks on the fender, rotational ability of the fender, and so forth.

C. Forces Exerted by Winds, Currents, Waves, Ice, and Floating Debris

Additional forces that act on moored ships and upon the fenders and main structures themselves that are taken into consideration only in those locations where they are severe, are those created by the action of winds, currents, waves, ice, and floating debris. Work has been carried out by the U. S. Navy to determine the effects of winds and currents on standard Navy ships.(3) Table I is a compilation of the effects on a single destroyer. In the original research, wind and current effects were obtained for nests of destroyers, and the reader is referred to the basic paper for that information. The maximum lateral force due to a 100 knot wind taken by itself does not seem to present any difficulty in design, but assume that the ship is bearing against a total of five fenders, each carrying 1/5 of the load, or 28 tons. If the fender is designed to carry a maximum load of 40 tons, there apparently is little danger of over stressing. As is usual when a ship is in

high winds, the vessel begins to roll and pitch violently, and relative rotational velocity is established with the pier. If the destroyer is approximately 2500 tons, and the relative imparted velocity is in the neighborhood of one foot per second, and assuming that a coefficient of 0.10 can be utilized because of the reduced mass of the ship that will be acting in rolling, the impact energy will be about 560 inch-tons, acting on five fenders, giving an impact energy per fender of 112 inch-tons. The fenders will normally take their impact loading through a deflection of from 4 to 6 inches. Therefore if for these particular fenders we use a deflection of 6" and a maximum force of 40 tons, the energy that can be absorbed will be 140 inch-tons. It can be seen that the fenders will probably not absorb the total impact energy. It is assumed that during the rolling operation, the side of the ship will be continually in contact with the fender and exerting a force of about 28 tons. The impact energy is encountered as the fender system stops the rotational velocity of the rolling ship. These loads can be reduced by a factor that is dependent upon the actual performance of the vessel during rolling. Any energy of impact due to the rolling or pitching of the ship that can not be taken up in the fender will have to be assumed by both the main structure and the ship. These facts must be taken into consideration when designing the main structure and the fender system. The same reasoning can be applied to the case of a ship that is subjected to a strong current, or when both currents and winds are acting. The analysis of each individual case must of necessity be a separate design based on the local conditions.

The study of the forces of waves acting upon marine structures has been the subject of many a learned treatise over the past centuries. Recent work has emphasized the importance of not underestimating the tremendous power of waves. It is not the purpose of this thesis to discuss or analyze the currently used or proposed theories regarding wave forces. To properly appreciate the destruction that can be accomplished by breaking waves, it is necessary to touch on the applicable factors. Pressures or forces imparted to a structure by waves can be accomplished by 1.) hydrostatic pressure of the head of water, 2.) kinetic energy of the moving water particles, 3.) vacuum caused by the rapid dissipation of the wave, 4.) a drag effect of the wave as it carries beyond the pile or caisson, and 5.) the impact of a floating solid object carried by the wave.(16)

Total hydrostatic pressure of a wave can be calculated by considering the horizontal projection of the pile or caisson as being acted upon by the water, with the resultant force acting at 2/3 the depth of water from the surface. The total force, in pounds, will be

$$F = \frac{1}{2} \times 62.4 \times \ell^2 \times d_p = 31.2 \times \ell^2 \times d_p$$

where d_p is the diameter of the pile in feet, and ℓ is the length under water in feet of the pile or caisson.

The kinetic energy of the wave or moving particles for each foot width of wave can be obtained from either the orbital or trochoidal theory of wave motion.(51)

$$\text{Orbital:} \quad E_k = \frac{w L_o H_o^2}{16}$$

where w is the unit weight of the fluid, L_o is $\frac{g T^2}{2\pi}$, H_o is the deep water height of the wave, and T is the wave period in seconds. The total energy of the wave can be obtained by multiplying the kinetic energy by two. In other words, the kinetic and potential energies are equal, and together make

up the total energy of a wave, so that $E_t = \frac{w\, g\, T^2\, H_o^2}{16\pi}$

$$\text{Trochoidal: } E_t = \frac{w\, L_o\, H_o^2}{8}\left[1 - \frac{1}{2}\left(\frac{\pi H_o}{L_o}\right)^2\right] = \frac{w\, L_o H_o^2}{8}\left[1 - 4.935\,\frac{H_o^2}{L_o^2}\right] \quad (16)$$

where $E_k = E_p = \frac{1}{2} E_t$. For waves originating in water of finite depths (as opposed to deep water originating depths) the energy will be

$$E_t = \frac{w\, L\, H^2\left(1 - \frac{M \cdot H^2}{L^2}\right)}{8}$$

where M = energy coefficient = $\frac{\pi^2}{\left(2 \tanh^2 \frac{2\pi d}{L}\right)}$.

Forces produced by the clapotis wave will give values essentially as shown in the above equations with the resultant acting at approximately still water level. It has been found by experiments and actual observation that a breaking wave will give much higher total forces. In a recent study(14) it was shown that the force of a breaking wave on a pile or caisson is about four times that to be expected from a clapotis wave. On flat surfaces this figure can be many times greater, where the entrapment of air by the breaking wave will give high shock values.(28) On a cylindrical surface the figure of four times the forces created by the clapotis wave should be used, and an increase of 50% in allowable working stresses may be used because of the transitory nature of the load. Additional information can be obtained from the work done by Morison, Johnson, and O'Brien.(29)

Minikin(28) has provided a formula for obtaining the total force that may be expected to be exerted on a flat surface such as a quay wall or mole

$$F = 0.96\left(1 + \frac{d}{d_o}\right)\frac{H^2}{L} + \frac{H}{70}\left(d + \frac{H}{4}\right) \text{ in tons per foot of wall.}$$

It is possible to assume that if a wave approaches a moored vessel so that the crest is parallel to the ship's side, then an extremely high force could be exerted simultaneously along the complete length of the ship. Depending upon the size and configuration of the vessel, the mass of the vessel, the total force of the wave, the inertia effect of the ship, the presence of wind and currents, the rolling effect of the ship, and other significant factors, it is possible for the vessel at the time of a breaking wave to cause a considerable kinetic energy to be imparted into the fender system. It is conceivable that this kinetic energy could be greater than that normally encountered during berthing of a ship. The exact amount of energy that will be thus transferred from the waves to the ship and then into the fenders must necessarily be the subject of study of the individual locality.

Information of incidents where waves have exerted almost unbelievable forces on structures is given by Minikin(28), two of which are:

1) An iron casing $1\frac{1}{2}$ inch thick and 18" in diameter, embedded in concrete 30 feet above sea level was sheared from its base by wave action.

2) A block of concrete weighing 70,000 tons was washed whole from its foundations into the harbor. This block would be about 100 x 30 x 14 yards.

The effects of ice flows or ice masses on fender structures as a result of the pressure of the ice on the moored vessels have not been evaluated to the knowledge of the author. Some work has been accomplished on ice pressures, but due to the fact that they are applied

slowly, it is more a problem of structural strength of the pier or wharf than of the energy absorbing qualities of the fenders. Therefore in the design of fender systems it considered that ice pressures are not a factor that should effect fender strength. The pressure being applied slowly will be transferred without energy absorption by the fenders to the pier structure where the forces will be taken up by the bracing and main foundation.

In a harbor where floating debris is to be expected that may cause damage to fender systems or main piling, protective features of design should be included. There is little that can be done to anticipate the forces that will result from collisions by debris, but for fenders it is logical to assume that they have been designed to withstand a much greater impact force than could be imparted by the debris usually found within any harbor. The real problem will be in local damage only, which in most cases can be readily repaired.

D. Fender Spacing

It is logical to assume that a single fender cannot be economically designed to take all of the kinetic energy transmitted by a ship; therefore it is necessary to provide sufficient fenders so that more than one acts. Depending upon the design, the spacing, and general configuration of the fender system, and the alignment of the pier itself the number of fenders acting upon a vessel as it approaches for mooring should range from three to ten. It will be the problem of the individual engineer to decide upon that particular criterion, based on the requirements of the local conditions. A problem commensurate with

the number of fenders acting is the one that deals with the loads imposed upon the main pile bents of the structure. Do not assume that the fender system will absorb all of the force of the advancing ship, for although if properly designed it will take most of the kinetic energy, there will be a portion of the energy in addition to the lateral force that will be transmitted into the basic structure itself. As the ship bears against the fender, causing a force to be applied, an equal force will be transmitted through the fender and will act on the pier. This force is not an energy that must be absorbed, but the reaction on the pier of the force imposed by the fender on the hull of the ship. Any structure acted upon by a force will deflect, and this deflecting will require performance of work, and thereby the absorption of energy, as can be seen in Figures 6 and 7. The amount of energy that will be absorbed by the main structure will depend upon its relative mass in comparison with that of the fender and the buffer system, and also upon the rigidity of the main structure. The energy of an approaching ship must be absorbed somehow, whether it is by the fender, the hull of the ship, the pier, or by damage and plastic deformation; therefore, if the ship is constructed so that it will absorb a constant percentage and the pier is rigid enough so that it absorbs only a negligible amount of energy, then the fenders if adequately designed will take up the remainder, neglecting the minor energy losses. In order to provide for sufficient rigidity in the pier and jetty structures raker or batter piles are used extensively. The energy of deflection will be absorbed by these piers, but in reduced quantities inasmuch as the deflection is

the result of longitudinal compression or tension of the raker or batter piles. Therefore as the pier is made more and more rigid the fender and the hull of the ship are required to assume more of the energy of impact.

E. Energy Absorbed by Pier

Stoyer describes the amount of energy that will be imparted into the pier that is not protected by resilient fenders as

$$E'_k = E_k \frac{M}{M + m}$$

where M is the mass of the ship and m is the mass of the pier structure. It can be seen that when the mass of the pier is large in comparison with that of the ship, the energy that is transmitted into the pier is greatly reduced. If an acceptable fender system is added to the pier the amount of kinetic energy that will be imparted into the pier ahd absorbed by it will be relatively small in comparison with the absorption when there are no fenders. If the pier is either rigid or of a large mass with a suitable fender system, the energy of impact will be absorbed by the hull of the ship and the fenders, with relatively little being transmitted into the pier.

It is usually assumed that the deck of a pier or wharf acts to distribute the load by shear in the deck panels to at least five main bents and possibly to as many as ten, so that the force applied to any one bent is comparatively minor. Stroyer recommends that the figure of ten bays for absorption of energy be used when constructing the pier deck of reinforced concrete. It is the author's opinion that the use of ten bays for a rigid reinforced concrete deck is reasonable, but that

this figure should be decreased as the rigidity of the deck decreases. As an example, a timber deck will transmit far less shear because of its ability to deflect more easily, so that it is considered that five bents should be the maximum for consideration in this case. In a composite type deck perhaps the number of bents would be increased to seven or eight depending upon the design and construction techniques used. When speaking of bents, it is assumed that the bents will be piles of timber, concrete, or steel, and does not refer to caissons or other supports that will permit more than perhaps a 15 to 18 feet span of the deck. Minikin's recommendation(28) of distributing the load over a length equal to twice the width should be considered when the pier is narrow as compared to its length or where the span between bents is unusually large. In order to carry the lateral horizontal thrust to as many bents as possible, some piers have been designed with a horizontal truss along the center of the deck and tied into the main pile bents.(52) The number of bents thus mobilized is proportional to the size and weight of the truss members used.

F. Batter Piles.

Figure 8 shows the standard method of arranging batter piling and the force and deflection diagram. Table II is a compilation of the various energy absorbing qualities of the batter piles. This table, compiled by Stroyer (45), is based on the assumption that the piling acts in either pure tension or compression, and does not take into consideration bending, nor is the limiting factor of soil capacity considered. Tschebotarioff (48), in some experiments with model dolphins,

Table II

LOADS, DEFLECTIONS, AND ENERGY ABSORPTION OF A PAIR OF 14 INCH SQUARE PILES WITH VARIOUS BATTERS AND STRESSED TO 500 POUNDS PER SQUARE INCH *

Batter of Piling	Parallel 1: ∞	1:5	1:4	1:3	1:2½	Pile Length, in feet
Allowable Mooring Load, F, in tons	6.68	17.25	21.3	27.8	32.7	5
	1.68	17.25	21.3	27.8	32.7	20
	0.84	17.25	21.3	27.8	32.7	40
Deflection, S, in inches	0.0094	0.051	0.041	0.0316	0.027	5
	0.150	0.204	0.165	0.1265	0.1057	20
	0.600	0.408	0.330	0.2530	0.215	40
Absorption, in inch-tons	0.0315	0.44	0.44	0.44	0.44	5
	0.126	1.76	1.76	1.76	1.76	20
	0.253	3.52	3.52	3.52	3.52	40

Note:(1) A combination of one vertical pile and one batter pile will have one-half the allowable mooring load, twice the deflection, and the absorption will be the same as the double batter pairs.

Note: (2) It can be seen that by altering the batter of one or both piles a given absorption can be obtained with the desired amount of deflection.

* After Stroyer, reference (45).

shows that in pull-over tests of three-pile dolphins with the piles in a straight line the soil pressures are such as to induce considerable bending stresses in the piles. In several cases the batter piling, designed for compression and tension by the classical methods, failed in bending at the ground line at loads greater than calculated. It is evident then that the method of considering the piles to act in pure compression or tension only is a relatively safe procedure, probably giving an additional safety factor in both the maximum stress and the absorption of impact energy. One important finding set forth in Professor Tschebotarioff's paper indicates that the load-carrying capacity per pile of a seven-pile dolphin is much lower than the unit pile load of the three-pile dolphin. Whether or not this feature will have any effect on the use of batter piling of a pier is still a matter of conjecture. It is possible that in the arrangement of pier supporting members where batter and main piling are driven in a cluster, a "dolphin" action may exist thereby conceivably reducing the loads that the piling will carry.

In determining the limiting values for compression and/or tension in the batter piling, Stroyer(45) in his analysis fails to take into consideration the fact that the soil is the limiting stress factor and not the material of the pile and its cross-sectional area. Minikin(28) properly assumes that for the allowable stress in compression the bearing capacity of the pile is the limiting factor, and for the allowable stress in tension he uses the bearing capacity minus the product of the area of the base of the pile times the unit bearing pressure of the soil. In other words, if the total load capacity of the pile is 30 tons, the cross-

sectional area is one square foot, the allowable soil bearing pressure is 1.5 tons per square foot, and the angle between the inclined piles and the vertical is θ, the total horizontal force, F, that two-batter piles will sustain will be

$$F = 30 \sin\theta + (30 - 1 \times 1.5) \sin\theta = 30 \sin\theta + 28.5 \sin\theta$$

but this leads to an unbalanced vertical force of 1.5 tons, so that the limiting load on the two pile group is 28.5 tons per pile or

$$F = 2 \times \sin\theta \times 28.5 = 57 \sin\theta$$

As a method of preliminary design and investigation the use of sketched deflected structures as suggested by Hardy Cross(10) is recommended. With practice adequate bending moment and shear diagrams can be obtained to a fair degree of accuracy, in addition to giving the designer a preview of the deflection probabilities of the fender system and pier. When using this technique, it should be remembered that the point of inflection of a beam tends to move toward the point of least rigidity. For purposes of computation a point of inflection can be considered as an imaginary hinge where the bending moment of the beam is zero. The author thinks that this method should be used to check any design of a structure not as a rigorous procedure, but to ascertain that the results are within acceptable limitations. To get the deflection that may be expected at any point, the area-moment principle can be used.

The amount of deflection of any pile or bent due to the effect of shear as compared to deflection caused by bending can be neglected in most instances where the length is greater than 10 times the depth or thickness of the pile. When the ℓ over d ratio is 10 to 1 then the deflection due to shear is only 3% of the total.

G. Depth of Fixity of Piles

Research on the design of anchored bulkheads accomplished by Tschebotarioff for the U. S. Navy (47) has given much information that can be extrapolated to include partially the effect on fender piles and main structural bents, regarding soil pressures and points of inflection. With the head of the pile hinged to approximate the anchored portion of a bulkhead, and the load applied somewhere between the hinge and the ground line, then it can be assumed that the point of inflection of the pile is close to the dredge or ground line. For a fender pile that is not fixed or hinged at the head but is cantilevered, the depth of fixity beneath the ground line is a matter of controversy. Terzaghi(46) suggests the formula

$$D_f = \sqrt[5]{\frac{216\ E\ I}{d_p\ m_h}}$$

where $m_h = \gamma_s \frac{K_p - K_a}{\delta}$, a dimensionless coefficient, and δ is the maximum deflection of the pile. Chellis(8) simply uses the value of 1/3 the total depth of embeddment for the depth of fixity, ignoring the fluff and the loose silt on the surface of the dredged bottom. The writer feels that this tends to give unrealistic values, for it fails to take into consideration the effect of the various types of soil, the consolidation of the silt, the type of pile, and numerous other variables.

Minikin(28), after carrying out tests on single piles, has reasoned that the position of "virtual fixity" is at a depth below the ground level a distance equal to 0.3 aD where "a" is a coefficient equal to a value from 0.75 to 0.70 depending upon the ℓ/D ratio. This will give values for fixity of from 0.210 to 0.225 of the depth of embeddment for the point

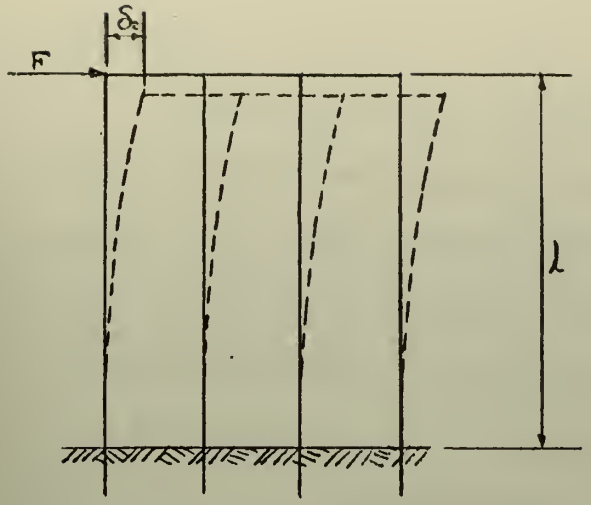


Figure 6 -- Deflection of pier without fender

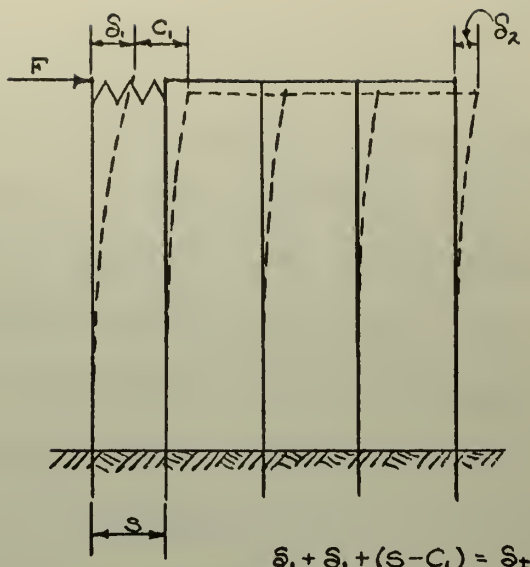


Figure 7 -- Deflection of pier with fender

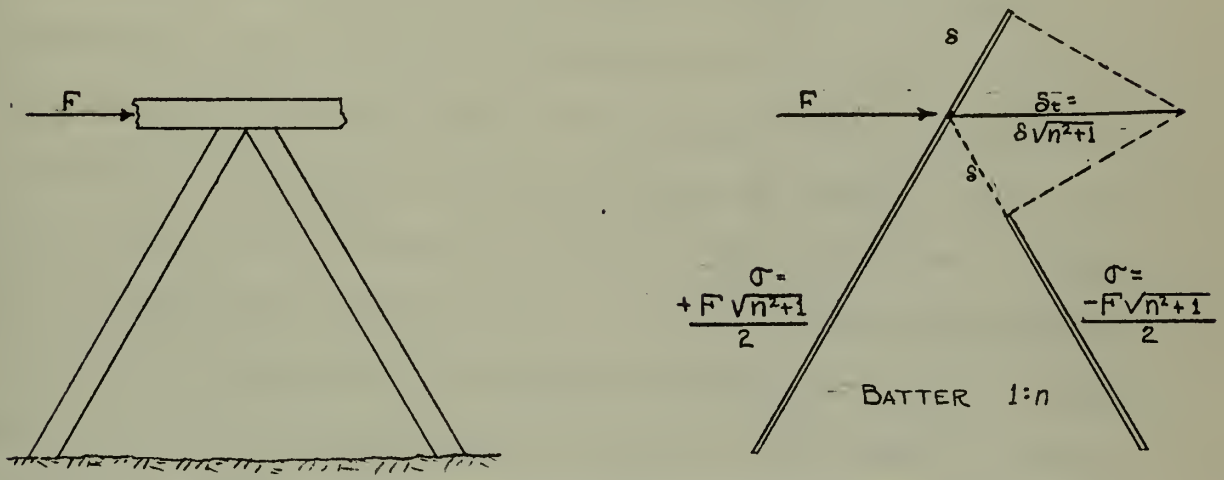


Figure 8 -- Deflection and force diagrams of batter piles

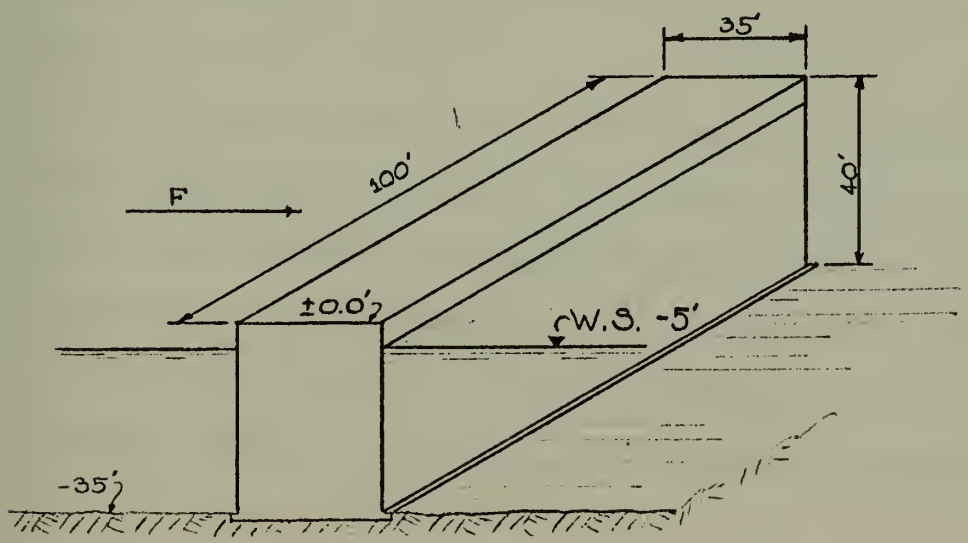


Figure 9 -- Concrete monolith section of a mole or caisson

of fixity.

Conclusions reached by Palmer and Thompson(34), and later substantiated by Palmer and Brown(35) indicate that the peak pressure (soil reaction) is greater than the passive pressure of the soil as computed under the classical theories. In addition they found that the point of maximum bending moment is relatively independent of the point of application of the force above the ground and the depth of embedment of the pile, and that the magnitude of the maximum bending moment in the pile is considerably less than usually computed by assuming a point of fixity. This is further indication that the theory of considering a depth of fixity of D/3 or as indicated by Terzaghi can be misleading and give values closer to the unsafe side when dealing with energy absorption. It is important to distinguish between the degrees of fixity of the end conditions of the pile at its head. If it has a large percentage of rigidity or is hinged then Tschebotarioff's method of assuming the dredge line in firm soils as the point of inflection should be used, but if the pile head is free of any restraint then the value of fixity given by Minikin can be used providing adequate safety factors are utilized to compensate for soil conditions, flexibility of the pile, and the findings of Palmer, et al.

In this particular field of soil mechanics a number of studies are still being carried on, and until the results are all published and analyzed it is recommended that computations be based on the least favorable assumptions of having the point of fixity close to the ground line, or to consider the point of inflection at or slightly below the ground line. To assume a depth of fixity that is too large will overstress the sur-

rounding soil and result in permanent plastic deformations which in subsequent deflections of the fender or bent piling will result in the piling being worked loose in the soil, or to cause the main structure to be moved out of line with possible local failures.

H. Periodic Oscillations and Earthquakes

Although there are few occasions when fenders are subjected to periodic vibrations, they are influenced by repeated loadings from waves, ships, and winds that can cause constant oscillatory stresses within the soil mass surrounding the piling. Repetitious loading of soil, particularly clay, in shear will result in lowered allowable design stresses. This feature of soil is similar to the fatigue of metals.

Fenders although not normally designed to handle the effects of earthquakes, will absorb the impact energies created by accelerations of the pier against the ship. The action will be reverse to that normally anticipated from fenders in that the ship will be the object with the inertia and the pier will be the moving mass with kinetic energy. The mass of the pier would normally be much greater than that of the ship, and the velocity imparted into the pier by the earthquake can be of a sizeable quality. Fortunately the horizontal movement induced in the pier is relatively small, so that the energy to be absorbed by the fenders will involve a momement of the fender usually less than its maximum travel or deflection. The energy of the pier obtained by the acceleration due to the earthquake will be dependent on the length of the piling or height of the pier decking above the ground level, the period of oscillation of the pier, the duration of the shock waves, and the mass of the pier com-

pared to the flexibility of the main piling. The ship's hull plating will absorb a portion of the energy and the movement of the ship will absorb an additional quantity.

I. Impact of a Ship Against a Quay Wall or Mole

The effect of the energy of a moving ship imparted to a gravity-type quay wall, mole, or solid pier will depend upon the constructional features of the structure. Where the mass of the quay, mole, or pier is large compared to the mass of the ship, little effect will be noticed on the structure, and where adequate fenders are employed the effect will be negligible. Several installations have been built using a bumper system rather than a fender system as a result of the harbor owners' thinking that the ship of necessity will have to dock very carefully or cause damage to itself. From the standpoint of the harbor owners this attitude is underatandable for it involves a saving of construction funds and reduces maintenance problems, but this type of protection to the pier can be disastrous to the ship. In European countries large monoliths of concrete or stone, or concrete caissons filled with rubble and capped are used in the construction of moles and closed piers. Assume a monolith of more or less standard size as represented in Figure 9 with the values as indicated, and a ship of 30,000 tons displacement coming into contact with the caisson at a velocity of 0.4 feet per second, which is a reasonable value for a ship of such a size. Then assuming that the ship will impart a minimum of 0.20 E_k into the caisson without damaging the ship itself, the nominal energy of impact of the ship will be

$$E_k = \frac{1}{2} \frac{30,000}{32.2} (0.4)^2 (0.2) = 14.9 \text{ foot-tons} = 179 \text{ inch-tons} = 400,000 \text{ inch-pounds}$$

The force that will act on the monolith is obtained by assuming that 50% of the ship's hull bears on the rubbing strip which is 100'x16" and can be stressed to a maximum of 5000 psi. Inasmuch as this is an impact loading an average wood can be stressed momentarily(3) to 5000 psi. This will give a maximum value of

$$F = 0.5 \times 5000 \times 100 \times 12 \times 16 = 48,000,000 \text{ pounds}$$

It is assumed that the hull plating can be loaded with an additional 5000 psi over that to which it is already stressed, without damage to the ship, then this figure will be the limiting stress. Taking energy as equal to the average force times the distance through which it travels,

$$E_k = 400,000 = F_a \cdot \delta = \frac{48,000,000}{2}$$

$$\therefore \quad = 0.0167"$$

which is the minimum distance that the monolith must move to absorb the energy of impact without failure of the rubbing strip. It can be seen that this distance is negligible. Consider also the effect of keying one monolith to another, friction at the base of the structure, and the fact that few captains would risk damage to their ships by approaching at a speed of 0.4 feet per second, and it will be realized that any movement of the caisson or mole section can be neglected. Although the force is large and will create large overturning or rotational movements, it is of extremely short duration. Even if the maximum lateral resisting force is the frictional forces, inertia of the water, and of the passive soil pressures, the movement will still be less than 0.1" and consequently can be ignored. If berthing is utilized on both sides of the mole then whatever slight movement may be found in one direction will normally be offset by a corresponding movement in the opposite direction.

If a fender system is designed for a solid, rigid structure, such as a mole, it must be borne in mind that the fender will accept all of the kinetic energy imparted by the ship, and little if any assistance can be expected from the mole structure itself. There need be no fear that this type of structure will move on its foundations unless it is attacked by extremely high winds accompanied by the forces of large breaking waves, such as in the case where the outer side of the mole is used as a breakwater for the harbor. There though is a completely different problem.

III. FENDER PILES AND DOLPHINS

A. Fender Piles

It is admitted that timber is probably the most efficient of materials for absorption of energy from an economical and structural standpoint, but there are restrictions on its use that limit its over-all effectiveness. Probably the most common fender used is the timber pile which is driven outboard of the main piling or caissons so that the ship must strike it instead of the pier. This pile can be free at the top, partially restrained, or bolted or pinned to the main structure. When the pile is free to bend and translate in any direction the energy of the moving ship will be absorbed, regardless of whether the energy results from longitudinal, lateral, or vertical motion. If the pile is partially restrained, that is allowed to move in only one direction, it will absorb energy effectively in bending only in the direction of movement. Usually this movement is permitted laterally only, requiring that rubbing strips, rotating wearing pieces, or metal plating be used on the piles as protection against longitudinal forces. Many designs call for bolting the top of the fender pile to the deck of the main structure, thereby reducing greatly its effectiveness. The fender acts as a cantilevered beam with a hinged support at its outer end. Considering this type of construction and assuming that the impact force of the ship is concentrated at the water level, with the pile being 35' long, with the water level at 0.0, the ground level at -25', and the pier deck at +10', the energy transmitted directly into the main structure is approximately 50 percent or more. It can be seen that when using a rigidly connected pile, the main

structure will necessarily have to be designed to support a large portion of the impact loading in addition to the lateral forces normally encountered.

B. Arch Fender Piles

Minikin tells of a method of using arch-action to increase the absorptive capacity of piling. The fender pile is driven outboard of the pier and instead of the usual inward batter, they are driven with an outward batter, so that the head of the pile is some distance from the deck, say about 2'-6". Then the pile is pulled back and the head fastened to the decking, giving the pile a slight arch. From the principles of arches it can easily be visualized how additional work is taken up by requiring the impact forces not only to bend the pile but also to overcome an axial thrust. The main structure is required to take both lateral and upward forces.

C. Fender Piles with Buffers

In the more recent designs using fender piling, a buffer of rubber, a spring, a hydraulic damper, or a rope mat is used between the top of the pile and the pier deck to absorb any energy that the pile will attempt to pass on to the main structure. Each of these buffer systems will be discussed individually later. When an effective buffer or damper is utilized, the main structure can be designed for lighter loads with a consequent savings of material and money.

D. Impact Loading for Design

It is the practice of many design offices to utilize a uniform lateral loading in the calculation of the effect of impact on the main

structure rather than ascertain the true forces that must be overcome. Knowing the actual forces of wind and currents as indicated in part by Ayers and Stokes(3) these loads can be used for economical designing with safety factors, providing adequate and efficient fender systems are utilized.

Let us assume that a stress of 1,500 pounds per linear foot of pier is used as an arbitrary design figure, to include wind, current, impact, and so forth. If the vessels using the pier are considered to be of the same size and characteristics as those described by Ayers and Stokes the following can be used:

Lateral Force due to winds (100 knots)	750 pounds/foot
Lateral Force due to currents (2 knots)	160 " "
Lateral Force due to ineffectiveness of fenders	50 " "
Total lateral force	960 pounds per ft.

or a saving of 540 pounds per linear foot of pier. It is this loading that determines the size and spacing of the batter piling. It can also require an increase in the size of the main bearing piling if they are expected to take any of the lateral load. Consequently, any saving in the total lateral load will result in decreased sections and increased savings in money and material.

E. Energy Absorption Calculations

To calculate the amount of energy a fender pile can absorb, the deflection and average applied force must be known, to satisfy the equation

$$\frac{1}{2} MV^2 = F_a \cdot \delta$$

Knowing the mass of the ship that will be using the berthing facility and assuming a maximum anticipated velocity the energy of impact can be derived, or using the assumptions of Robertson(39) that stipulate a maximum impact energy of 400 inch-tons and an accident limit of 1200 inch-tons regardless of the size of the ship, the force F, can be obtained by equating the impact energy of the vessel to the energy absorption characteristics of the fender.

1. Cantilevered Fender Pile. Using a cantilevered fender pile, see Figure 10a, the deflection of the beam can be obtained by elementary strength of materials to be

$$= \frac{F_a \cdot \ell^3}{3\ E\ I}$$

then equating input energy to absorbed energy and substituting

$$\frac{1}{2} MV^2 = F_a \quad \frac{F_a \cdot \ell^3}{3EI} = 400 \text{ inch-tons}$$

or $$F_a^2 = 400 \ \frac{3EI}{\ell^3} = \frac{1200\ EI}{\ell^3}$$

Using a 14" diameter douglas fir pile 40'-0" long the average force will be

$$F_a^2 = (1200 \times 1{,}600{,}000 \times 1890)/(40 \times 12)^3 = 14.6$$

$$F_a = 3.83 \text{ tons (this is the average force)}$$

$$F = 7.66 \text{ tons}$$

It is usual to assume that this force will be taken by three to ten piling depending upon their spacing. For this example we'll assume that four piles will be acting, so that the force per pile will be approximately 1.0 ton. The deflection that will take place is

$$= \frac{F_a \cdot \ell^3}{3EI} = \frac{(1.0 \times 2.000)(40 \times 12)^3}{3 \times 1{,}600{,}000 \times 1890} = 27.3"$$

or over two feet. The deflection varies as the cube of the length, so that the energy absorbing qualities of the pile also follow the same proportion.

2. Fender Pile Free to Translate but not Rotate. If the pile is fixed at the top so that it is free to translate but not to rotate as shown in Figure 10b, then the deflection will be of the following order

$$= \frac{F_a \ell^3}{12\ EI}$$

which is one-fourth of the deflection expected if the pile were completely free at that end, and an equal force is applied. Using similar computations as with the free-ended pile, it is found that for the same dimensions and impact energy the force exerted on the structure is 7.65 tons. This gives approximately 2 tons per pile if it is assumed that the same four fenders are acting. The deflection of each pile then is 13.65". Here again the energy absorption capacity and the deflection is proportional to the cube of the length. The deflection is one-half that of the free-ended pile while the applied force is twice as great.

3. Fender Pile Hinged to Pier Deck. The calculation of forces in a fender pile that is fixed at the head is not quite as easy, for a portion of the load is transferred from the head of the pile into the pier structure. Therefore, the main bents must assume a portion of the energy, reducing the effectiveness of the fender system. Figure 10c represents this condition. If the impact load of the ship is applied to the fender at the water surface, or $\ell/3$ of the length of the pile from the decking, the immediate load applied to the deck of the structure will be about 0.52 F or approximately one-half of the total. The total energy

load will be absorbed by the bending of the fender and the bending of the piling in the main bents of the pier. Because of the number of main piling acting, the deflection of the entire structure will be small. The maximum deflection of the fender pile can be found by use of the formula

$$\text{max.} = \frac{F}{3EI}\left(\frac{\ell}{3}\right) \frac{\ell^2 - \frac{\ell^2}{9}}{\left(3\ell^2 - \frac{\ell^2}{9}\right)^2} = \frac{2F \cdot \ell^3}{187\ EI}$$

Equating the deflection to the impact energy we find that the average force, F_a, of the above example will be

$$400 = F_a \frac{2F_a \ell^3}{187\ EI}$$

or $$F_a^2 = 456$$

and $$F_a = 21.4 \text{ tons}$$

$$F = 42.4 \text{ tons}$$

Using the same four fenders to carry the force, the unit fender load will be 5.4 tons, which will give a maximum deflection of 4.7", at 5/13 measured from the level of the deck. This value does not take into consideration the deflection of the main structure, but assumes it to be rigid enough so that the energy it absorbs is taken up with minor or negligible movement. This is not necessarily the case, for with such a large force being applied the pier will have to be large and massive to deflect only a negligible amount. Each case must be studied in its own merits. It is suggested that the designer refer to Minikin(28), Cheskoff(9), or Anderson (1) for specific details on the distribution of loads and deflections within large piers.

If the fenders are erected so that the head of the pile is bearing

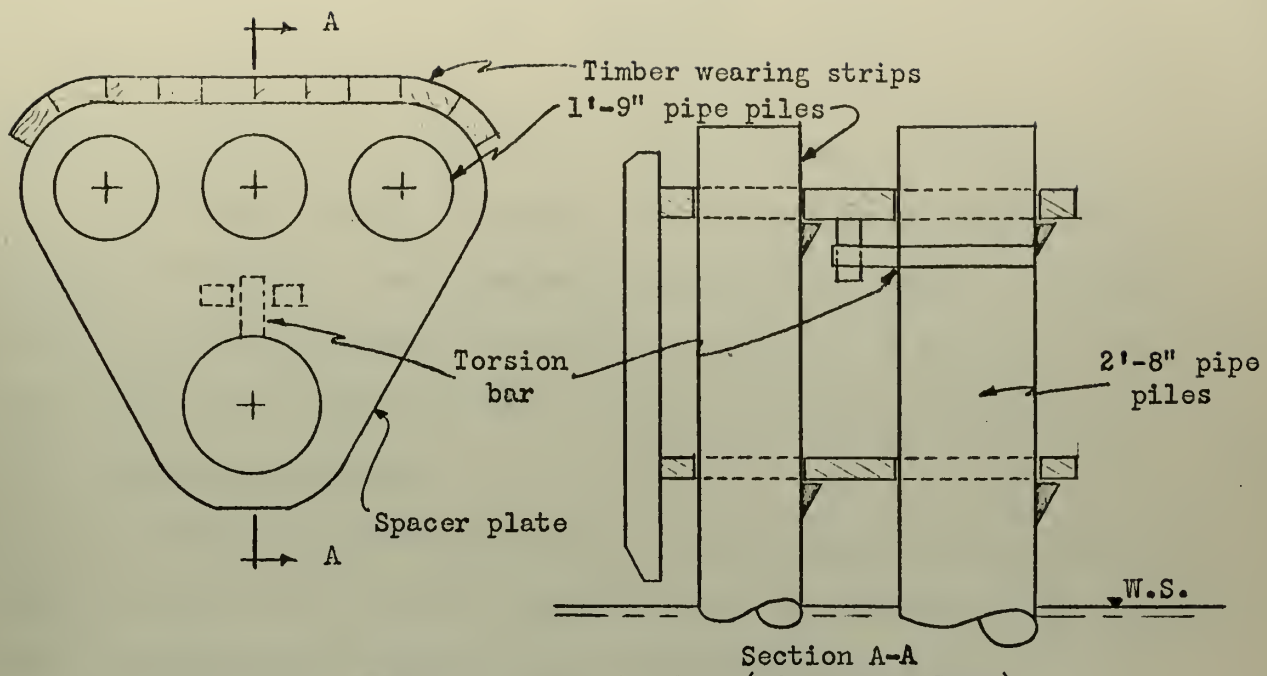


Figure 13 -- Mannesmann-type dolphin (after Risselada)

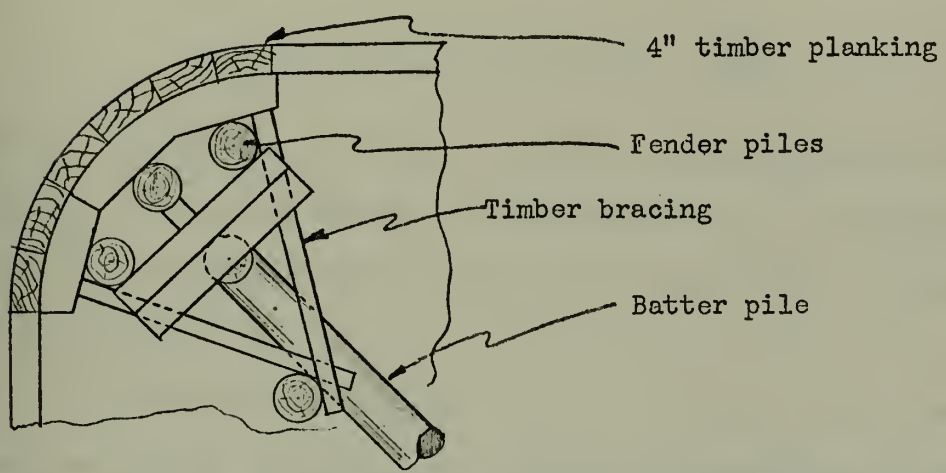


Figure 14 -- Corner fender for timber piers

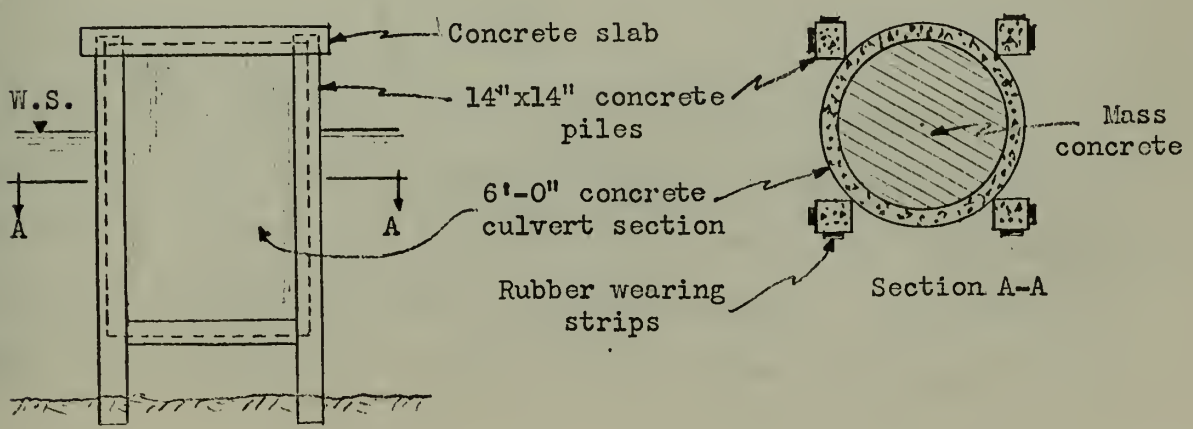


Figure 15 -- Massive concrete dolphin using precast concrete piles and culverts

against the deck or some portion of the pier causing the structure to take a portion of the direct impact, then the main bents must be appropriately designed. A more reasonable commonly used design is to install a buffer between the head of the pile and the pier. If properly designed this buffer will absorb most of the energy imparted to it by the fender.

F. Maximum Unit Stresses

When providing fender piles for a pier, especially ones that will carry vertical loads as well as absorb energy, the designer should investigate thoroughly the stresses in each representative pile for all forces that may be applied. Chellis(8) uses the formula

$$\sigma = \frac{P}{A} + \frac{P(\delta \pm e_1 \pm e_2)}{I} + \frac{M_b C}{I}$$

The author suggests that where applicable the pile should be checked in addition for torsion due to the longitudinal force or twisting caused by a ship as it rubs against the fender while still having a component of forward velocity.

The amount of energy a material can absorb in pure tension or compression without deforming can be found by computing the area under the stress-strain curve within the elastic limit

$$E_a = \frac{1}{2} \frac{\sigma_a}{E}$$

where σ_a is the maximum allowable working stress and E is the modulus of elasticity of the material. When calculating the deflection that can be withstood by a fender it is usual to increase the working stress well over the limits normally established in structural design. As an example for a point load at the center of a simply supported span, the stress is $\sigma =$

12 ec/L^2. Certain types of lumber of the more common grades such as douglas fir can be stressed to 5000 psi in impact, or in the case of the stronger woods such as greenheart, the allowable stresses during impact have been boosted as high as 11,000 psi. Robertson(39) considers greenheart as the most efficient fendering material regardless of what it is compared with. The author agrees that timber is an excellent fendering material, and if used properly can provide excellent protection to a waterfront structure. It has been the author's experience with timber fenders of douglas fir that they will give very good service providing they are properly designed, installed, and maintained. They are very susceptable though to damage from abrasion by ships, the attack of marine borers, weathering, and deterioration from certain types of harbor scum. At one station the author found that timber fender piles or frequently used piers had to be replaced on the average of once every one and one half to two years. Part of this abnormally high maintenance can be blamed on the locale and on the mooring procedures of the pilots.

G. Pile Materials

It is not intended by the above discussion to indicate that only timber can or is used for fender piling. In recent construction both steel and concrete have been utilized with considerable success. These materials are nearly always faced with timber or rubber rubbing strips to prevent localized damage to the ships, such as scraping of the paint, tearing off of projections, etc. Steel shapes of varying cross-sections have been used, such as H-piles, pipe piles, railroad rails, box sections, sections of sheet piling welded back to back, or a combination of these. Steel is sus-

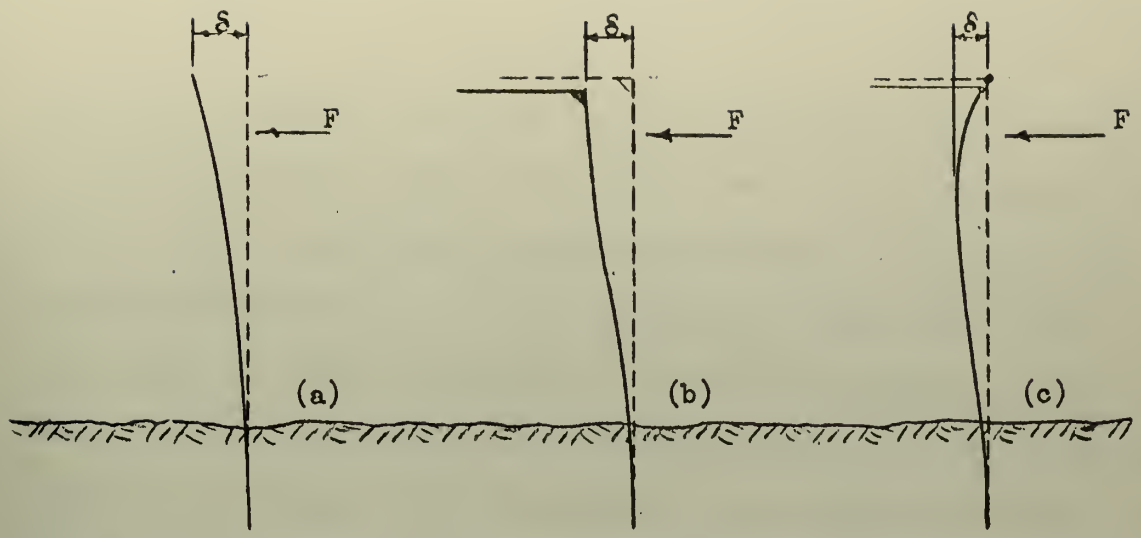


Figure 10 -- Various arrangements of fender piling

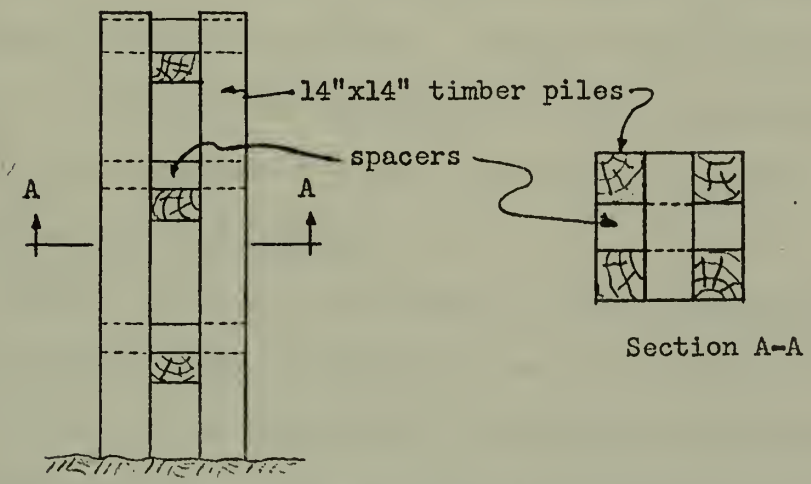


Figure 11 -- Multiple-pile fender (after Minikin)

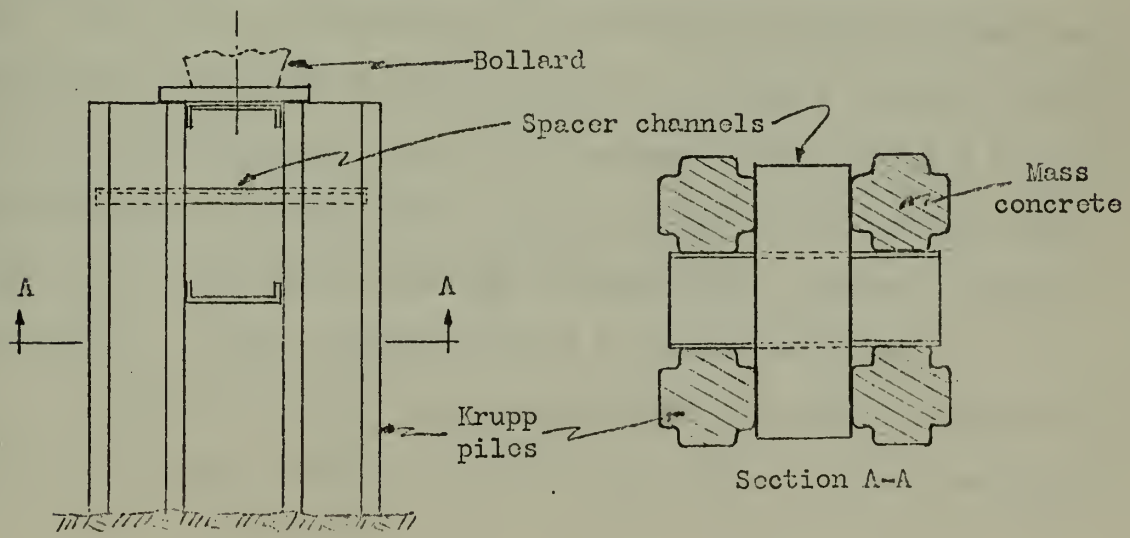


Figure 12 -- Krupp pile dolphin

ceptible to denting or permanent bending with increased deterioration due to stress corrosion. Concrete has usually been used in the form of cylindrical or square reinforced or prestressed piling, but it lends itself to future construction because of the capability of many varied forms. Concrete though is highly susceptible to scaling and chipping. Little use has been made of prestressed concrete fender piling, although some sources maintain that because of its flexibility it would make an excellent system. There are still too many unanswered questions regarding the action of prestressed concrete to be able to attempt a rigorous analysis to determine its energy absorbing capabilities. Because of the ability of prestressed concrete to withstand bending without the hairline tension cracks forming makes it a good candidate for use in waterfront structures.

H. Multiple Piles and Dolphins

Multiple piles are used often to provide additional energy absorption and strength characteristics that can not be obtained from single piles. Actually these multiple pile formations although used as fenders are in effect dolphins. Figure 11 shows a multiple pile fender using square timber piles with spacers.(27) Many European ports have made use of multi-pile structures of steel sections for dolphins primarily, but in a sense also for fenders. Figure 12 represents a shape designed for use with Krupp steel piles(23), while Figure 13 shows one of the Mannesmann dolphins such as is used at Amsterdam, Holland.(38). Figures 14 and 15 show examples of timber fendering and of a concrete dolphin.

An example of design of a dolphin built as a part of the pier and therefore acting as a fender is shown in Figure 16. This work was accom-

plished in Venezuala in 1948.(22) This particular arrangement leaves the main structure free from impact forces because of the flexible walkway or connecting pier is relatively slender and does not transmit the shock. Shield(41) in 1895 showed several methods of accomplishing the same purpose, except he used a reinforced pier head as an integral unit, permitting the rigid pier head to assume all of the impact. Examples are shown in Figure 17.

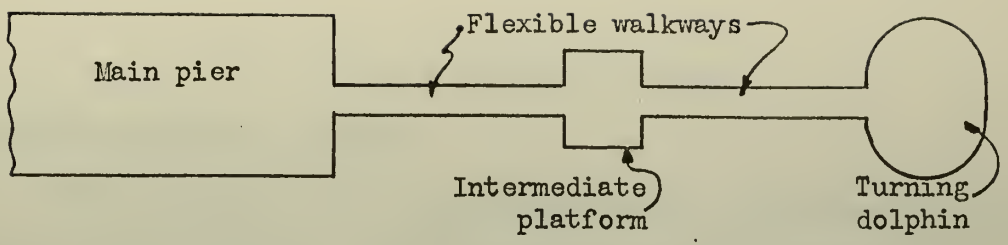
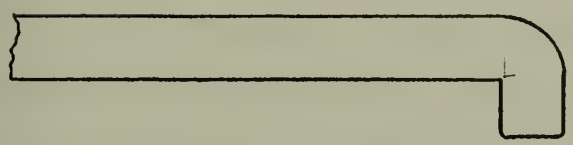
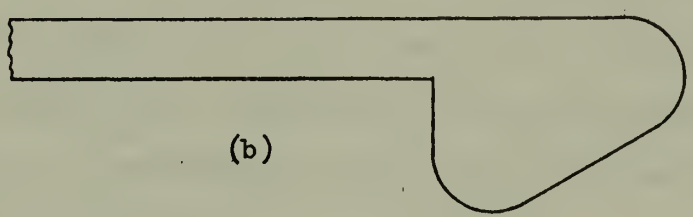
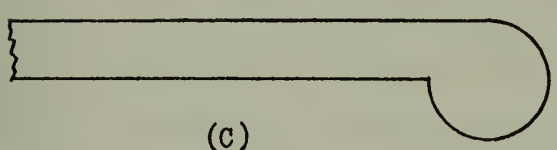


Figure 16 -- Oil-loading pier in Venezuala







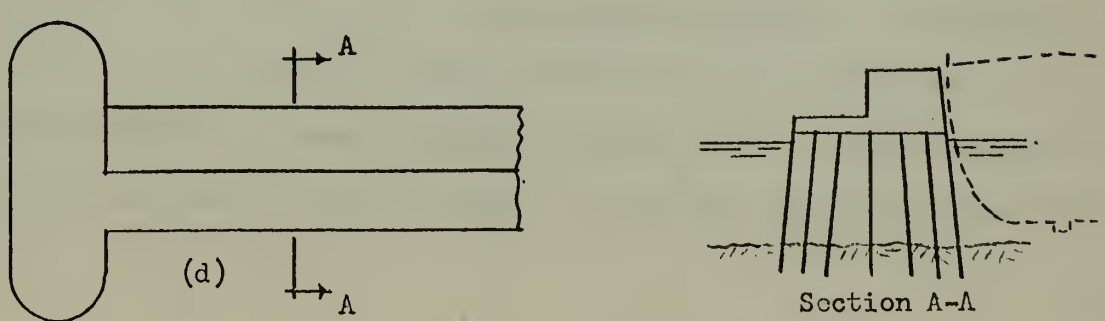


Figure 17 -- Strengthened pier heads to withstand impact (after Shield)

IV. THE USE OF RUBBER IN FENDERS

A. Characteristics of Rubber

When speaking of the necessity of having resiliency in fenders, the use of rubber comes to mind. It has been only recently, within the past decade or two, that the use of rubber has extended to the waterfront where it has been incorporated in fenders. Rubber has shown itself to be adaptable to many different shapes and forms for absorbing impact. It has for years been used as isolators to insulate against acceleration, shock, and vibration in aircraft, electronic gear, and automobiles. It has proven itself reliable, relatively inexpensive, and easily obtained, and in addition enjoys the trust of the users.

Probably the first and best known method of using rubber for fenders was to hang old truck tires along the pier or quay wall. A refinement was to wrap the tire with manila line to give it additional stiffness and wearing qualities. It was only a short step from the tire to the multitude of modern rubber fenders and buffers now in use. Rubber is now used primarily as a compression or shear device for energy absorption, with some very practical schemes being utilized.

Rubber, like any other engineering material, has its short-comings and its advantages. In its natural state it is subject to deterioration by hydrocarbons such as gasoline and oils that may be floating on the top of the water of the harbor; it is deteriorated by light and high temperatures (in excess of about 158 degrees Fahrenheit); and is attacked by micro-organisms.(53) By using synthetic rubbers, most of these disadvantages can be overcome to a great extent. It has been stated by Iredell(20)

that "within limitations, which grow narrower each day, the failure of a rubber product because of the chemical reaction of oxygen, ozone, sunlight, oils, and various substances can be placed on faulty choice of compound." He goes on to say though that rubber is susceptible to failure due to fatigue in tension and shear, but that this is not so in the case of compression. One excellent characteristic of rubber is its damping ability. Although not too important in the use of fenders, the fact that the material loses a large portion of its stored energy by hysteresis losses makes it desirable for use where rebound is not desired.

The simplest method of using rubber in fenders is to place a block of sufficient dimensions between the head of the fender pile and the deck of the pier to be protected, as illustrated in Figure 18. The rubber will act in compression and should be so designed that it will absorb the required amount of energy when it has deflected an amount equal to 50% of its original thickness. Andri(2) found that a rubber block under pure compression will fail when it has been compressed to about 30 to 35% of its original thickness. Therefore, if compression is designed not to exceed 50%, a safety factor of about 1.6 will be realized. It is presumed that a fender pile using a backing of rubber will act substantially like the one shown in Figure 7, where the impact load at the deck level will be absorbed by the rubber. Another arrangement that may be used is one where there is a clear distance between the pile head and the rubber bumper. This will allow the pile to absorb the initial impact by bending and the remain-

der will be taken by the rubber. The rubber is used as a buffer to absorb the remaining energy that the pile is unable to handle by itself.

B. Laminated Pads or "Sandwiches"

In 1948 Horsfield(19) reported on the results of tests performed on rubber buffers made by laminating rubber and steel into a multi-decker sandwich. He used 16 gauge steel plates to which the rubber was bonded and then stressed the pads to failure. The plates failed in tension before the rubber failed in compression. This can be explained by the shearing stresses that are set up when the rubber expands laterally due to the Poisson effect and is restrained from moving by the bond to the plate. Figure 19a shows the arrangement of the sandwich type buffer, and Figure 19b illustrates the effect of the shearing stress set up by the expanding rubber. Table III is a compilation of the results of these tests. Horsfield stated that there was no noticeable movement of the pier itself during the impact tests. This is important, for his readings were taken using the pier as a reference line by extending a scriber from the deck to record the movement on a piece of cardboard attached to the fender, in much the same way as pile driving records are kept. The results therefore are open to conjecture as to their accuracy. It is well to note that a 10% error in the estimated speed of the approaching ship will give a change of 21% in the impact energy. It may also be that in computing the nominal energy of the vessel, the coefficient determining the amount of energy taken by the ship's hull was excessive. The figures though give a good picture of the trend of how the bumpers react to impact.

C. Admiralty Fender Unit

A fender using a block of rubber as a bumper will still be subjected to the longitudinal forces for which the rubber will be little or no help. Therefore it is desirable to design a buffer that will absorb lateral, longitudinal and torsional forces. The Admiralty in England has devised a unit wherein the rubber is bonded to two steel plates and mounted to both the head of the pile and the deck as shown in Figure 20. The area of the rubber can be found by using an allowable stress in shear of 160 pounds per square inch. One plate of the "sandwich" is fixed to the deck of the pier and the other secured to the head of the pile, so that movement in any horizontal direction is restricted with an accompanying absorption of energy. Table IV provides the load and energy absorption capacities of the Admiralty fender.

In addition to the Admiralty buffer, several other similar units have been developed, one of which is shown in Figure 21. Inspection of these installations after they had been in use for two years indicates that they are standing up very well, although several engineers have expressed uneasiness about the effects of rust on the bond between the rubber and the steel plates, and possible failure due to torsion and fatigue. Proponents of the bonded rubber buffers are convinced that these features are not critical and have been overcome. It will take the experience of several more years of use of bonded rubber sandwiches before a completely acceptable answer can be reached.

It is admitted that the problem of deterioration of rubber can

Table III

COMPILATION OF TEST RESULTS OF A RUBBER "SANDWICH" TYPE BUFFER

USED WITH A FENDER PILE (Refer to Figure 19)*

(1) Test No.	(2) Impact velocity ft/sec.	(3) Theoretical energy absorbed by fender pile in inch-tons	(4) Buffer No.	(5) Maximum compression in inches	(6) Maximum load in tons	(7) Total maximum load in tons	(8) Theoretical energy absorbed by buffer in ft-tons	(9) Total energy absorbed by buffers in ft-tons	(10) Total of columns 3 and 9	(11) Nominal E_K of ship in ft-tons	(12) % of nominal E_K absorbed
A	0.8	0.2	1	0.03	1	131	-	3.4	3.6	5.0	72
			2	0.02	1		-				
			3	0.88	82		2.2				
			4	0.68	47		1.2				
B	1.0	0.5	1	0.05	2	141	-	3.7	4.0	7.8	51
			2	0.03	1		-				
			3	0.96	98		2.8				
			4	0.60	40		0.9				
C	1.0	0.2	1	0.20	1	124	-	3.0	3.2	7.8	41
			2	0.10	5		-				
			3	0.90	87		0.4				
			4	0.51	31		0.6				

* After Horsfield, reference 19.

Table IV

LOAD AND CAPACITY FOR VARIOUS SIZES OF

THE ADMIRALTY BUFFER SYSTEM

(Refer to Figure 20)*

Size of rubber buffer		Load to give 45° deflection in shear, pounds	Capacity, inch-pounds
Diameter, inches	Thickness, inches		
9	3	10,000	15,000
14	3	25,700	38,600
14	6	21,400	64,200
21	4	53,600	107,200
21	6	53,600	160,800

*After Smee, reference 43.

easily be overcome by production control, but to preserve the external portions of the sandwich plates of steel, they will have to be made of non-corrosive metals or surface protected so that continued maintenance will not be required. The buffer unit is fastened to the pier and to the pile head with bolts or screws, which are a potential source of future corrosion. It is recommended that a non-corrosive or galvanized metal be utilized both for the plates and for the bolts. Objections have been raised that the metal of these fenders will not last for over five or ten years if made of structural steel; it is inconceivable to the author that an efficient fender system should be ignored or not used even though it will be effective for twice the time of standard fenders.

D. Raykin Fender Unit

An innovation of bonded rubber plates where the rubber acts in shear only has been developed and is known as the Raykin buffer.(15)

Figure 18 -- Rubber Buffer and Fender Pile

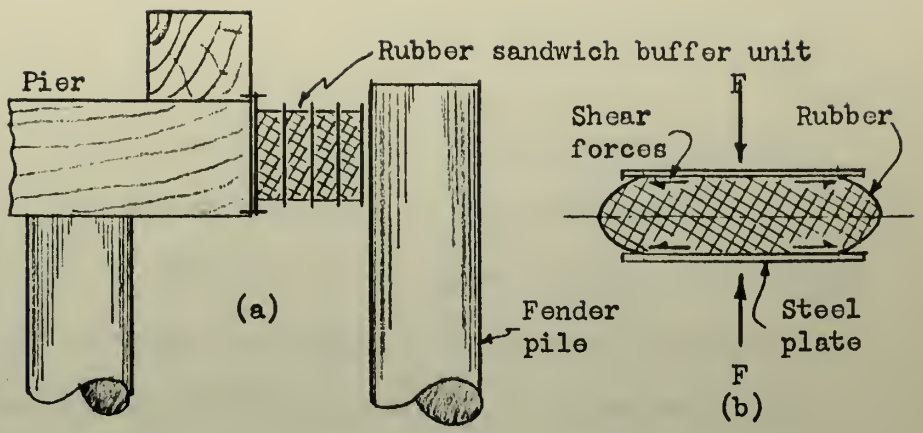


Figure 19 -- "Sandwich-type" Rubber buffer used with a fender pile

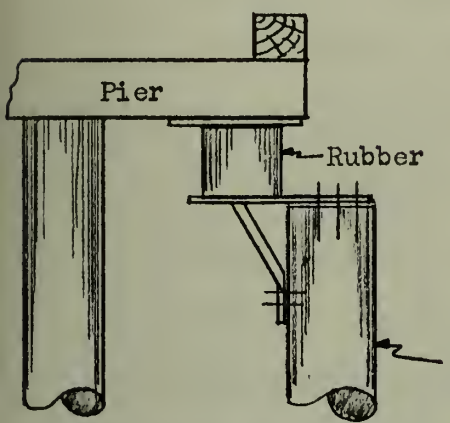


Figure 20 -- Admiralty rubber buffer unit

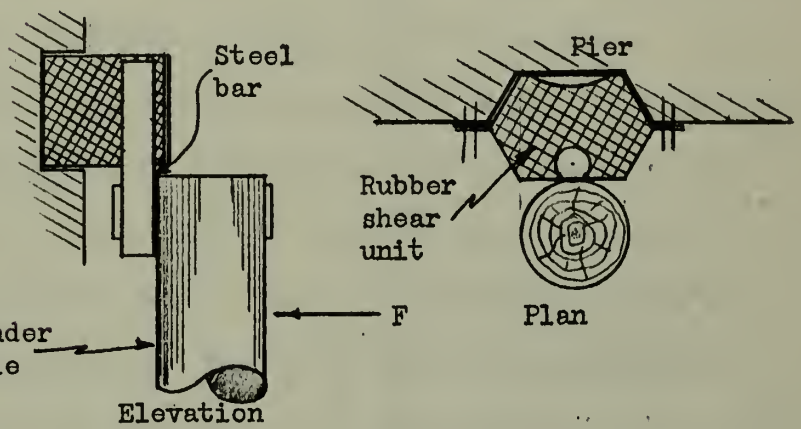


Figure 21 -- Rubber buffer unit for use with fender piles

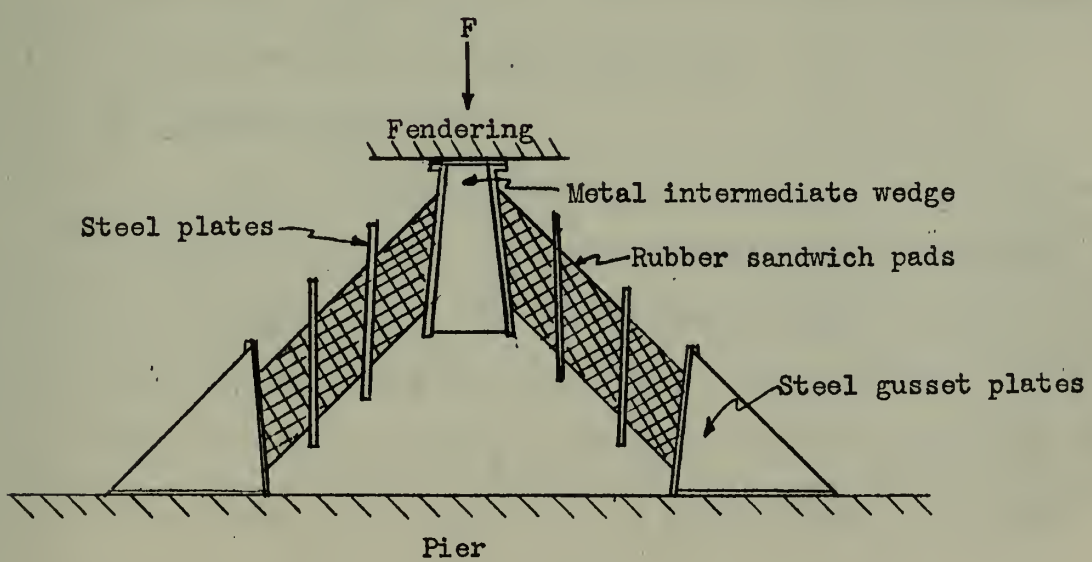


Figure 22 -- Raykin Fender Buffer Unit

It can be easily adapted to either vertical or horizontal mounting, and the number of units can be increased to take any desired load. Table V gives the load capacities for the number of units used. Figure 22 is a sketch of this fender and Figure 23 is the energy-deflection and the load-deflection curves for the buffer. This fender follows the requirements of an ideal system in that as the deflection increases the rate of energy absorption increases. A sufficient number of units can absorb large quantities of energy. They are designed so that the fender "bottoms" when the rubber is stressed to 45° in shear. It is felt though that before acceptance of this buffer system is considered, an improvement of the method of attaching the plates should be made unless non-corrosive metals are used. There are many crevices in which rust can progress, and if not properly protected the cost of maintenance would be excessive. The Raykin unit is essentially the same as the Admiralty type, for it uses the same general principle differing only in method of attachment. It should be noted that for the Raykin unit, a unit shearing stress of 100 psi was used instead of the 160 psi used in the British counterpart.

E. Neidhart Fender Unit

Still another development is the Neidhart fender buffer(20)(15) that makes use of the compression characteristics of rubber. It works on the principle of a lever acting against rubber cylinders or bushings that will compress as the lever turns. Figure 24 shows two different types of this device that can be used as fender mechanisms. Table VI is a compilation of the forces and energies that one of these units can

Figure 23

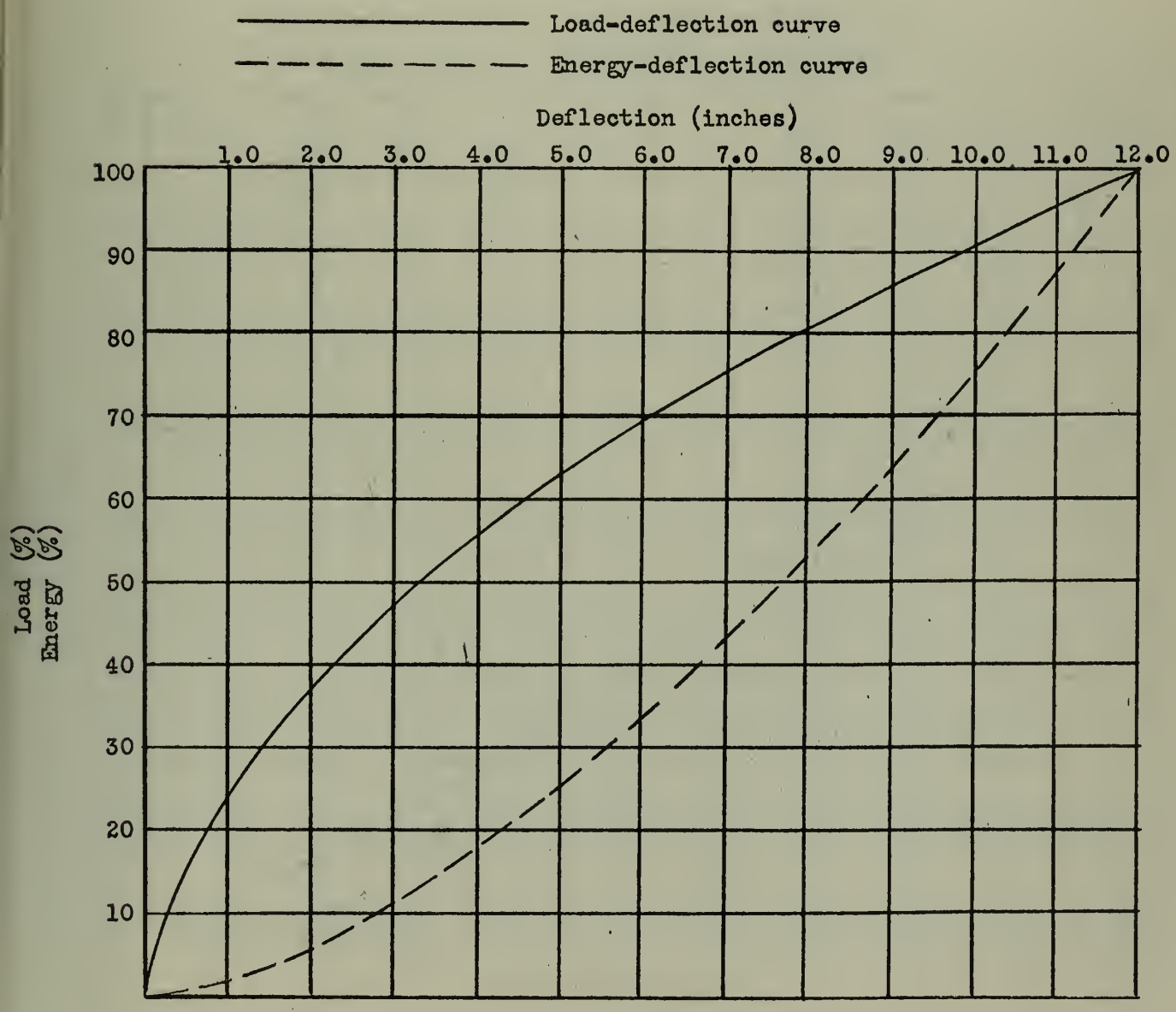
Characteristic curve

for

RAYKIN

Fender Buffer

100% energy = 0.640 x Load x Deflection



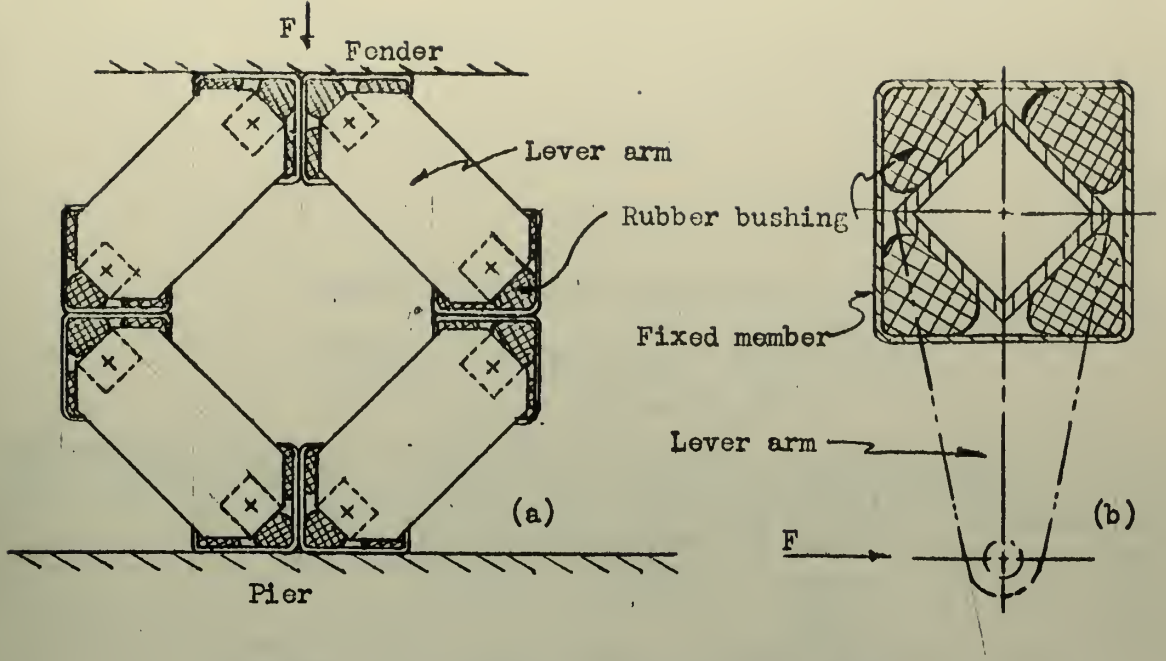


Figure 24 -- Neidhart fender buffer units

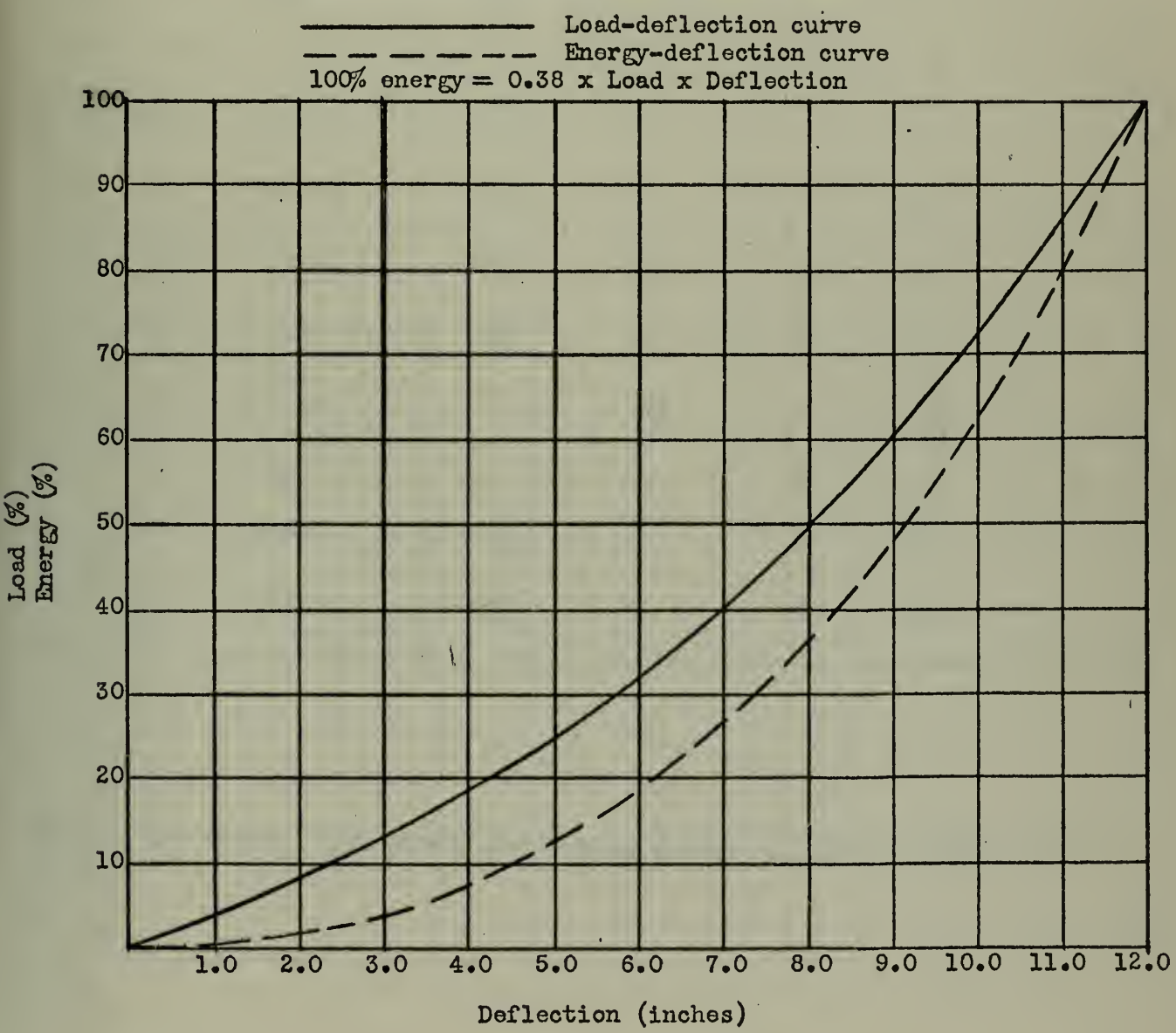


Figure 25 -- Characteristic curves for Neidhart Fender Buffer

Table V

CAPACITY AND ENERGY-ABSORPTION DATA, AND

DIMENSIONS OF THE RAYKIN BUFFER UNITS

(refer to Figure 22)*

Unit No.	Capacity, tons	Energy absorption, inch-tons	Height of individual rubber pad inches	Width of individual rubber pad inches	Thickness of individual rubber pad inches	Plate thickness, inches	Maximum deflection of unit, inches
1	5	25.5	$7\frac{1}{4}$	7	2	$\frac{1}{8}$	8
2	10	51.0	10	10	2	$\frac{1}{8}$	8
3	15	115.0	$12\frac{1}{2}$	12	3	$\frac{1}{8}$	12
4	20	154.0	$14\frac{3}{8}$	14	3	$\frac{1}{8}$	12
5	25	192.0	$16\frac{1}{8}$	$15\frac{1}{2}$	3	$\frac{1}{8}$	12
6	30	230.0	$17\frac{5}{8}$	17	3	$\frac{1}{8}$	12
7	35	269.0	19	$18\frac{1}{2}$	3	$\frac{3}{16}$	12
8	40	307.0	20	20	3	$\frac{3}{16}$	12
9	45	346.0	$21\frac{1}{2}$	21	3	$\frac{3}{16}$	12
10	50	384.0	$22\frac{3}{4}$	22	3	$\frac{3}{16}$	12

* After the General Tire and Rubber Company Report No. 257-A, reference 15.

Table VI

CAPACITY AND ENERGY ABSORPTION DATA, AND

DIMENSIONS OF THE NEIDHART FENDER UNITS

(refer to Figure 24)*

Unit No.	Capacity, tons	Energy absorption, inch-tons	Diameter of rubber bushing, inches	Length of rubber bushing, inches	Maximum deflection, inches	Length of lever arm, inches
101	5	15.2	1.39	6 3/4	8	5 3/4
102	10	30.4	1.39	13 1/4	8	5 3/4
103	15	68.4	2.25	12	12	9
104	20	91.0	2.25	15 7/8	12	9
105	25	114.0	2.25	19 7/8	12	9
106	30	136.7	2.25	23 7/8	12	9
107	35	159.5	2.25	27 3/4	12	9
108	40	182.0	2.25	31 3/4	12	9
109	45	205.0	2.25	35 5/8	12	9
110	50	224.0	2.25	39 5/8	12	9

* After General Tire and Rubber Company Report No. 257-A, reference 15.

absorb, while Figure 25 is the load-deflection and the energy absorption-deflection curves. Iredell remarks, "The fields of application of the Neidhart spring are practically unlimited. Generally, it can be employed wherever a torsional spring would be practical." The only objection to this type of apparatus for use as a fender is the difficulty in getting to the interior for corrosion maintenance, but this again can be overcome by utilization of non-corrosive metals. An advantageous feature of the Neidhart fender is its ability to take the longitudinal loads at the same time that it is overcoming the lateral impact loads. Vertical loads for the most part will be taken by the pier after being transmitted directly by the buffer.

F. Rubber Tubing for Fendering

A more simple method of fendering by rubber has been developed utilizing heavy rubber tubing. Developed by one of the major rubber companies it can absorb fairly large quantities of energy of impact per foot of length. Usually hung along the side of a quay wall or solid pier, it can also be used as a buffer behind waling or fender piles. Methods for use are shown in Figures 26 and 27 with the load and the energy absorption capacities given by the graphs, Figures 28 and 29. This rubber tubing has the advantage of being easy to use, of requiring no extensive additional construction, can be replaced rapidly and inexpensively without use of special equipment, and of having a relatively low unit cost. In using the tubing for horizontal fendering, the designer must be careful that forces set up are not great enough to damage the hull, particularly on a ship that is framed longitudinally.

Additional methods of using rubber for fenders are presented in Figures 30, 31, 32, and 33.

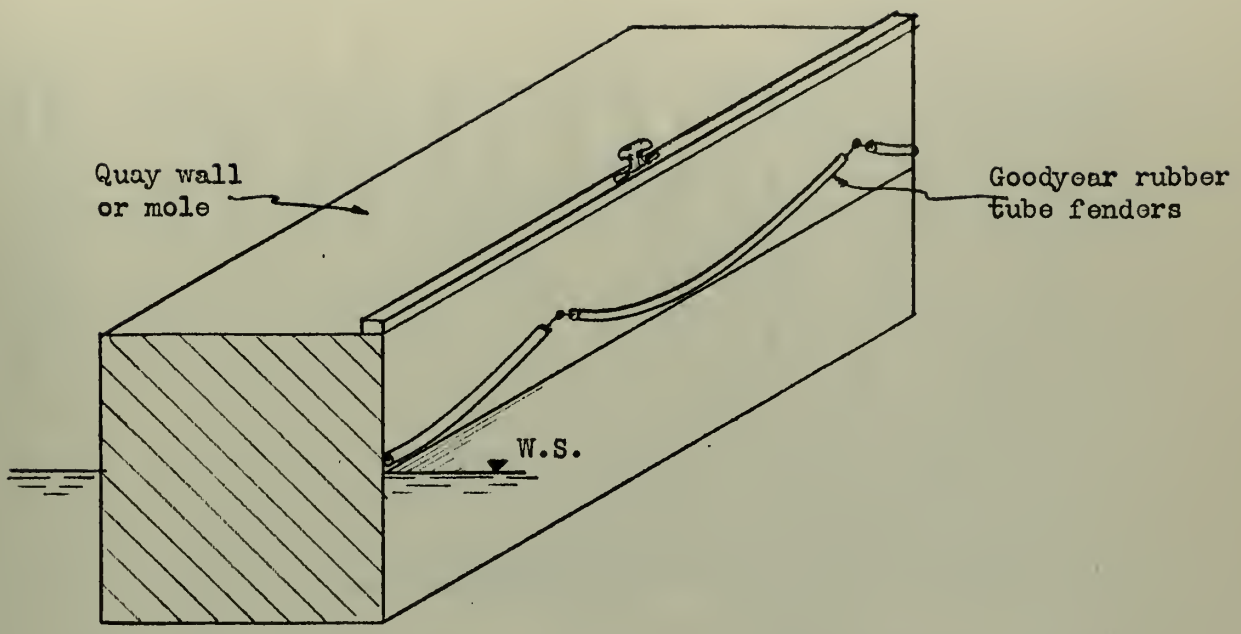


Figure 26 -- Goodyear Rubber Tube Fenders used on quay wall or mole

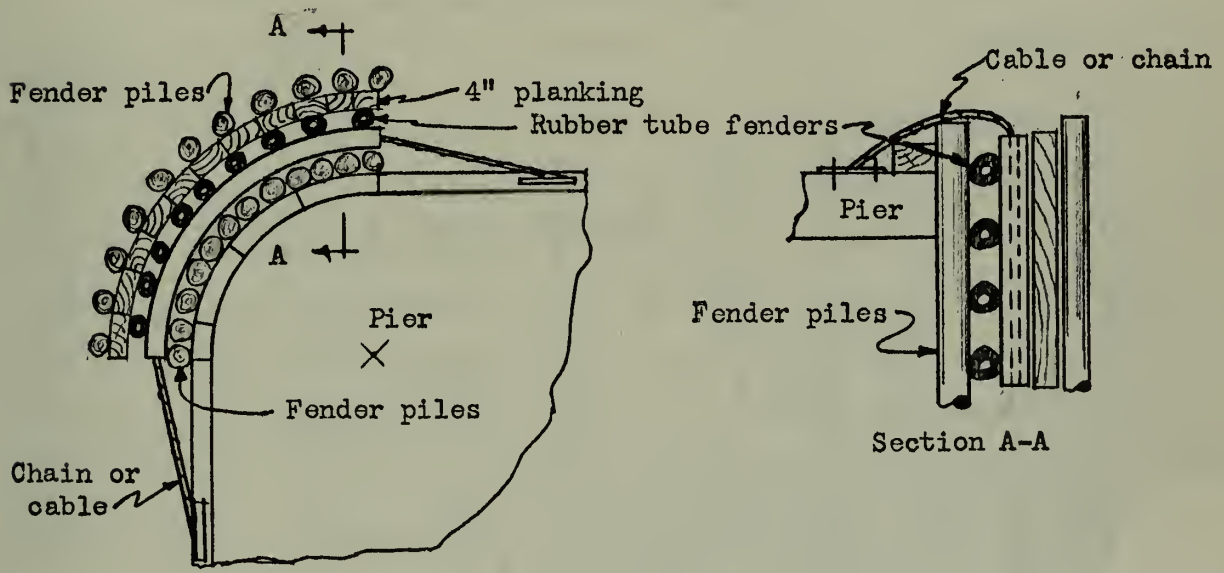


Figure 27 -- Goodyear rubber tube fendering used as a buffer system for corner protection of a pier (from A. L. L. Baker)

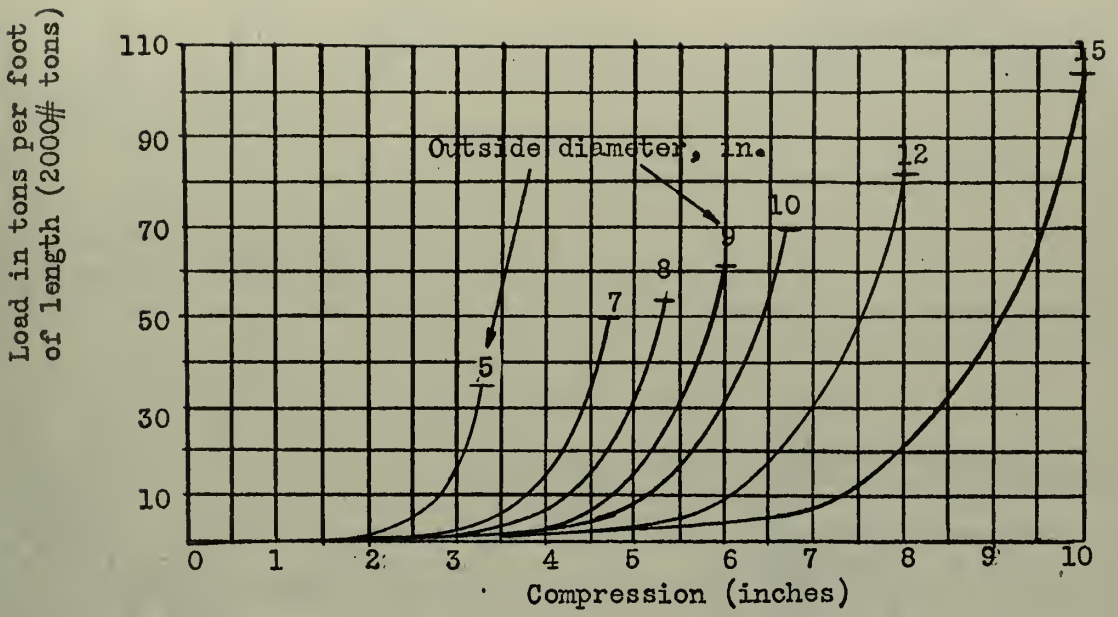


Figure 28 -- Load compression curves for cylindrical Goodyear rubber tube fenders

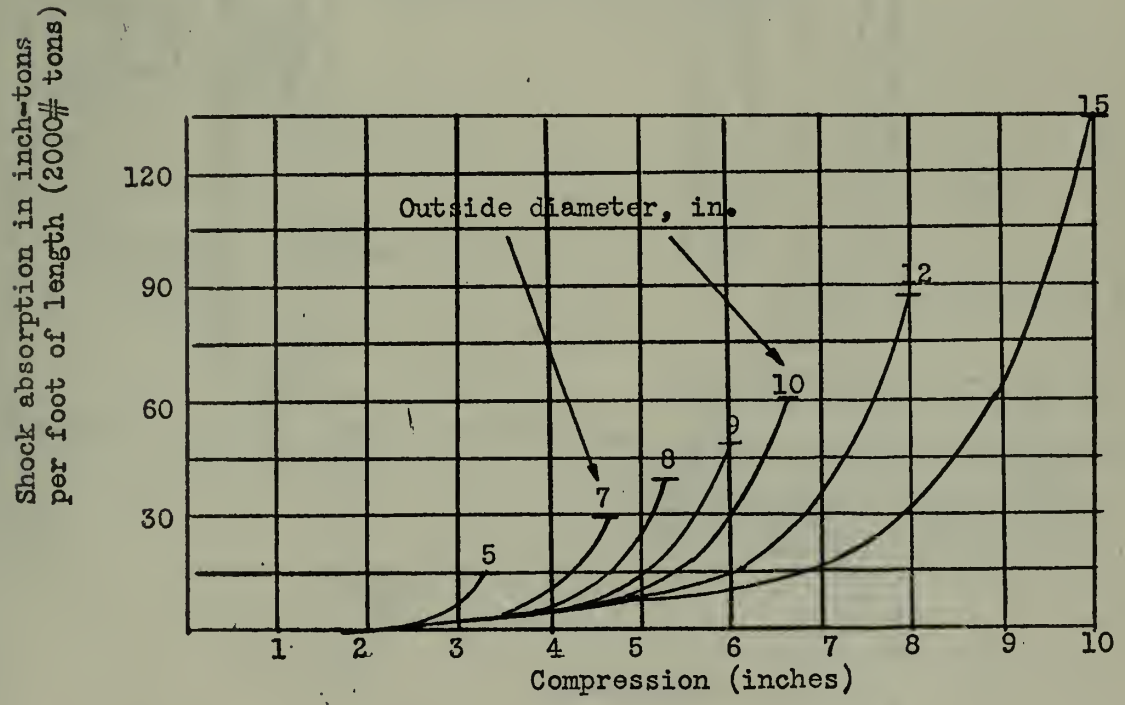


Figure 29 -- Energy absorption properties for cylindrical Goodyear rubber tube fenders

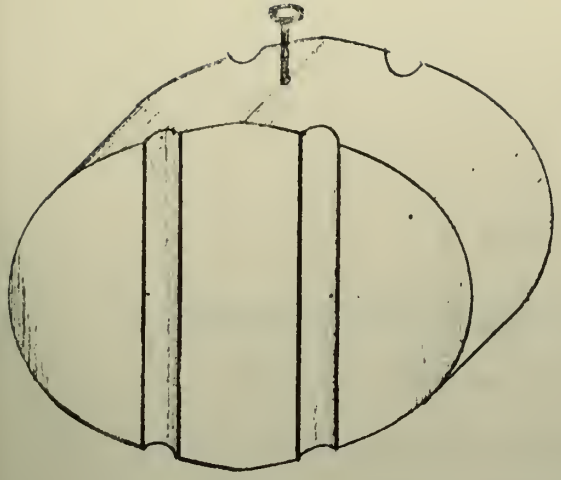


Figure 30 -- Avon India Rubber Co. buffer unit

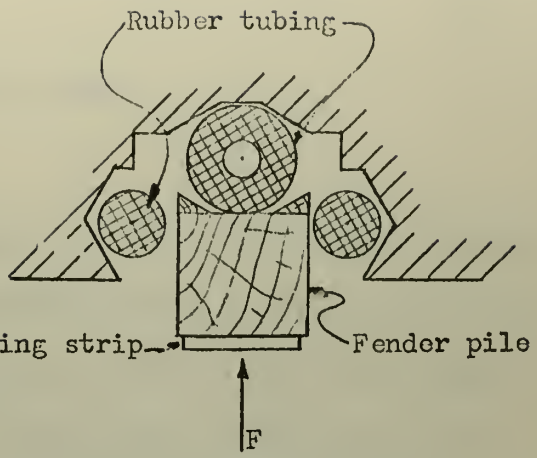


Figure 31 -- Rubber tubing used as buffers

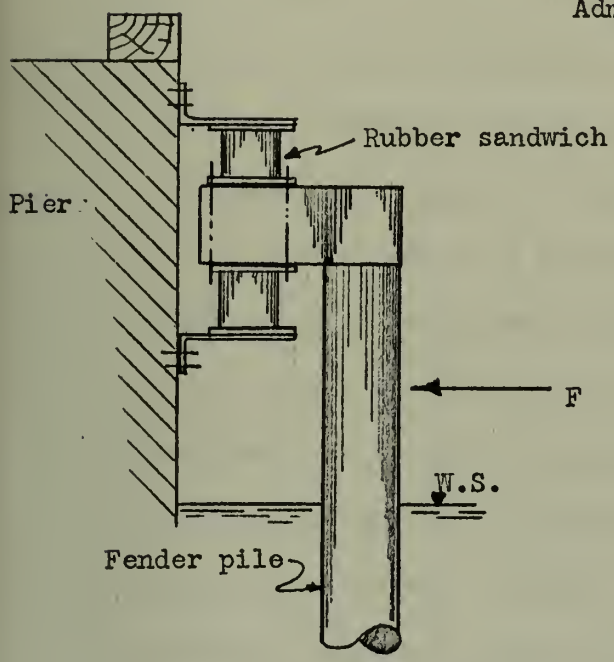
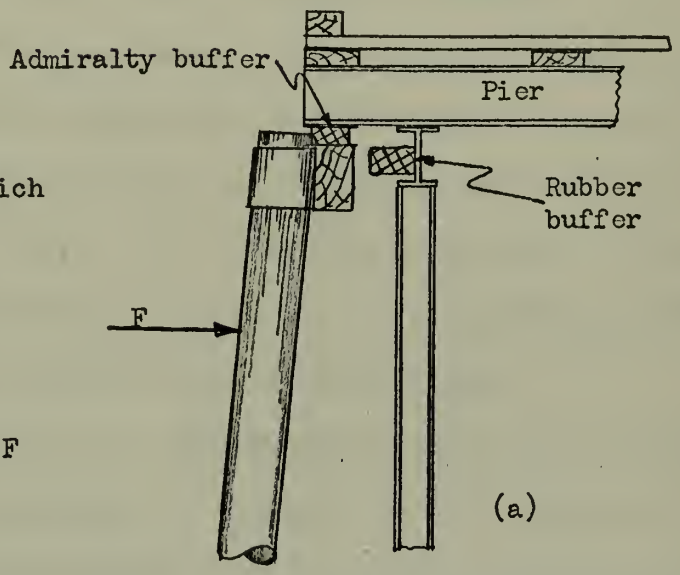


Figure 32 -- Raykin single sandwich fender unit



Section of Admiralty fender

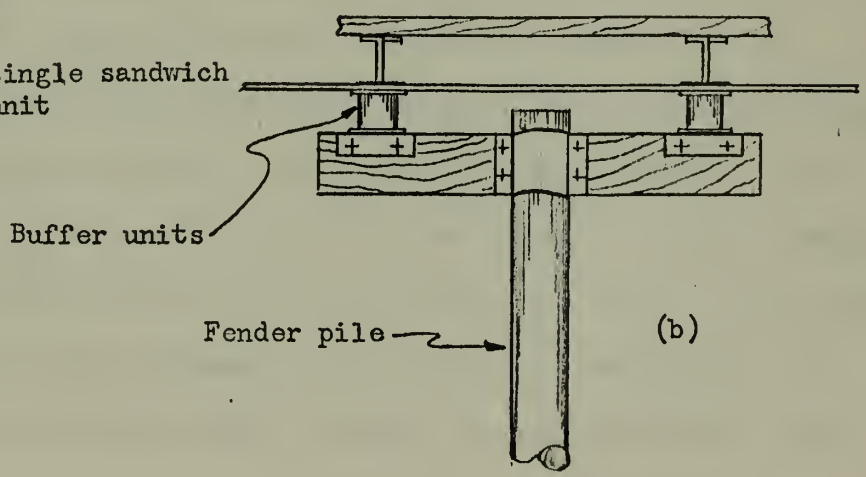


Figure 33 -- Application of the Admiralty fender

V. SPRING BUFFERS FOR FENDERS

A. Characteristics of Spring Buffers

When the need for heavy-duty energy absorption was first apparent in the construction of fenders, the designers turned to the use of steel springs. A notable early use of springs was in the walls of the locks of the Panama Canal.(7) and this was not the first time they were employed. In theory, springs are excellent energy absorbing mechanisms but in actual practice they have proved expensive to maintain. They have a tendency to jam in their guides; they need periodic lubrication; they are highly susceptible to salt water corrosion; they are usually specially fabricated for the particular installation; and heavy lifting equipment is required to replace a broken or corroded spring. A spring will absorb energy as a function of the square of its deflection thereby fitting one of the major requirements of the ideal fender.

Over a period of from ten to fifteen years springs will provide good service, if properly maintained. Spring fenders installed on a pier in Pearl Harbor(17) in 1926 apparently gave satisfactory fendering protection until about 1941 when they began to develop troubles due to the increased usage and reduced maintenance brought on by World War II. These same springs continued in use until recently when they were replaced by a fender of different design. When the springs were removed it was found that the metal had corroded away from the original one inch diameter so much that the sound steel remaining was about the size of a lead pencil. When justifying the use of springs it is necessary to analyze the comparative installation and maintenance costs of substitute fenders along

with those of the spring actuated fenders. The type of pier construction should be taken into consideration, for with certain designs spring fenders would be more of a hazard than an aid.

It is recommended that when considering the use of springs for fenders that they be designed especially for the work. Several firms deal with the manufacture of spring assemblies specifically designed for use in contact with salt water spray, where there will be little opportunity for maintenance. A typical spring assembly is shown in Figure 34, and the various sizes are listed in Table VII with the energy absorption capacities of each.(49) Attention is invited to the fact that three springs are employed for each unit. Although not depicted in the illustration it is possible to design this type of spring assembly so that it is mass sensitive to a certain extent and also so that the rate of energy absorption will increase as the load increases. This can be accomplished by making the smallest spring longer than the other two, with the intermediate spring longer than the heavy one. The lengths of each will depend upon what reaction the designer requires as the springs deflect. For a light ship, the long, light spring will absorb the initial energy, so that as it strikes the heavier springs enough of the impact will have been absorbed so that high unit stresses will not be set up. For the heavier ships, the initial contact with the small and intermediate springs will be relatively small and the majority of the impact will be absorbed by the heaviest spring.

B. Spring Design

In most instances it would be uneconomical to utilize only one spring in a unit; it is preferable to use two or more springs to take

Table VII

DIMENSIONS AND ENERGY-ABSORPTION CAPACITIES OF VARIOUS TYPES OF COMMERCIALLY AVAILABLE SPRING BUFFER UNITS (refer to Figure 34)*

Spring unit type	Length of unit, inches	Resistance, tons	Range of action, inches	Energy absorption capacity inch-tons
Short range	9	20	2	20
	13	30	2 1/2	37
	17	50	3	75
Long range	29	10	7	28
	36	30	12	135
	47	20-25	16	135

* After George Turton Platts and Co., Ltd., reference 49.

maximum advantage of the mechanism. To calculate the allowable loads, and the resiliency of a single spring the following formulas may be used:(25)

a. For a cylindrical helical spring of circular cross-section

$$F = \frac{\pi d_s^3 \sigma_v}{16 r k}$$

$$E_a = \frac{F}{2} = \frac{\sigma_v^2 V_s^2}{4 G k^2}$$

$$= 64 nr^3 F/d^4 Gk = 4\pi nr^2 \sigma_v/Gkd$$

where n = number of coils, and k = $[(4c-1)/(4c-4)] + 0.615/c$; where $c=2r/d$

b. For a cylindrical helical spring of rectangular cross-section

$$F = 2 b^2 h \sigma_v/9rk$$

$$E_a = F \cdot \delta/2 = 4 \sigma_v^2 V_s (K^2 + 1)/45 Gk^2$$

$$= 7.2 \pi nr^3 F(b^2 + h^2)/b^3 h^3 Gk$$

where $K = b/h$, $k = [(4c-1)/(4c-4)] + 0.615/c$; where $c = 2r/b$

When using springs, the spring itself should be completely enclosed in a casing that allows deflections but yet seals the case against leakage of salt water into the assembly and retains the lubricant inside the casing. In addition, a fitting must be provided so that the lubricant can be injected at regular intervals to prevent corrosion and seizure. It is a good idea to consider the future maintenance of the unit by placing it in such a position on the fender or pier that it can be easily reached for repair and lubrication, and so that it may be easily removed and replaced without using heavy lifting equipment and requiring a great deal of work. One of the main objections to the use of springs is the difficulty in working on them because they are placed in such hard-to-reach locations.

C. Use of Springs

Springs, like rubber, are not restricted to use with fender piles, but can be incorporated in hung or gravity fenders or can be used with other media such as hydraulic, rubber, and pneumatic units. The manner in which a spring is used is pretty well delineated by its shape and its susceptibility to corrosion; therefore it must be as far above the sea water as possible, and even out of the spray range if practicable. They are normally used only in compression, accepting only those loads that are parallel to its axis, thereby requiring a special rig to prevent the longitudinal loads from jamming the sliding casing. This tendency to jam can be overcome somewhat by providing hinges at each end of the unit, or while leaving one end completely free have the other end securely fastened

so that the mechanism is cantilevered out from the pier. This last will allow a partial slipping of the fender piling along the surface of the unit transmitting essentially only the loads that are normal to the pier.

A hung fender system employing a series of springs as used by Du-Plat-Taylor(15) is illustrated in Figure 35. The wales between the individual fenders are hinged so that they allow full deflection of the springs before they are brought into play, indicating that the fender can take up additional energy over and above that which the springs can absorb by utilizing the bending of the timber. In this particular fender each spring could take a force of 30 tons in a movement of 3 1/2" , making the entire fender capable of carrying a total load of 90 tons. It is suggested that in order to make this system more efficient and spread over a larger number of fenders, the wales might be rigid so that when one fender deflects, the others will begin to deflect and absorb energy commensurate with the deflection of the wales.

The spring fender system discussed earlier that was used on a pier at Pearl Harbor is shown in Figure 36.(17) This is the more common type of installation used, although the use of springs with a single connecting wale such as shown in Figure 37 is extensive. The latter is similar to the one used on the Panama Canal.(7) Examination of the Figure 37 will serve to illustrate one of the inherent defects of using a single wale with springs. The weight of the wale produces an unbalancing couple that is resisted only by the chain when the casing is at its outward extention; unless the chain is the correct length, the casing will tend to cock either up or down depending on the tightness of the chain. After the fit of the

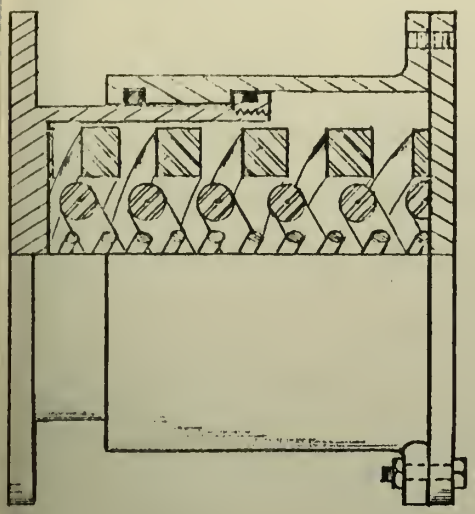


Figure 34 -- Spring buffer unit for use with fenders

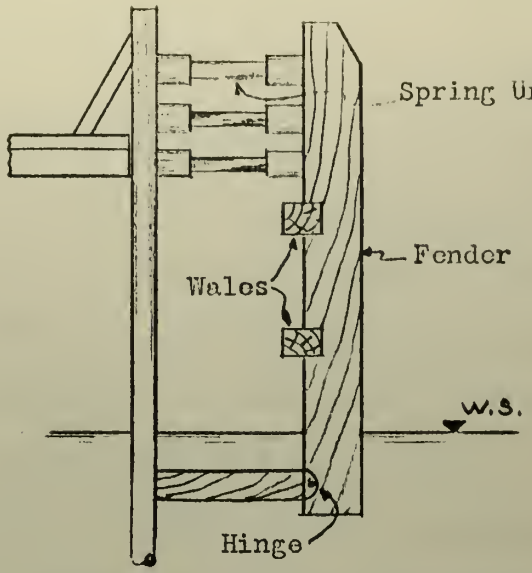


Figure 35 -- Fender incorporating spring buffers

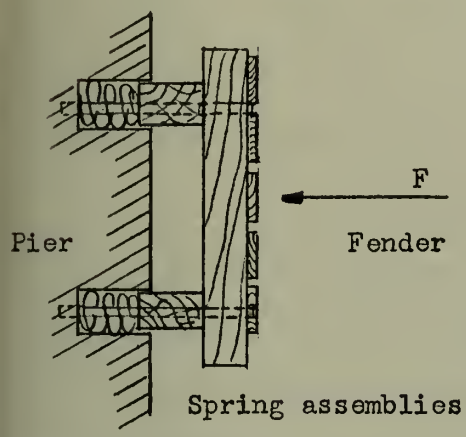


Figure 36 -- Fender using two spring units

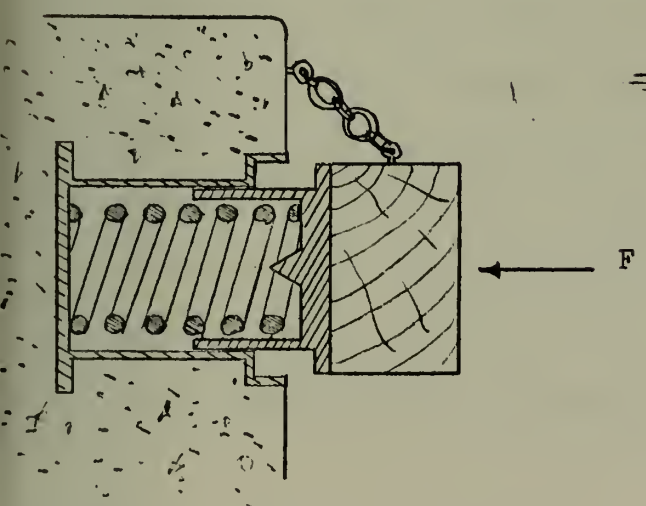


Figure 37 -- Single spring fender

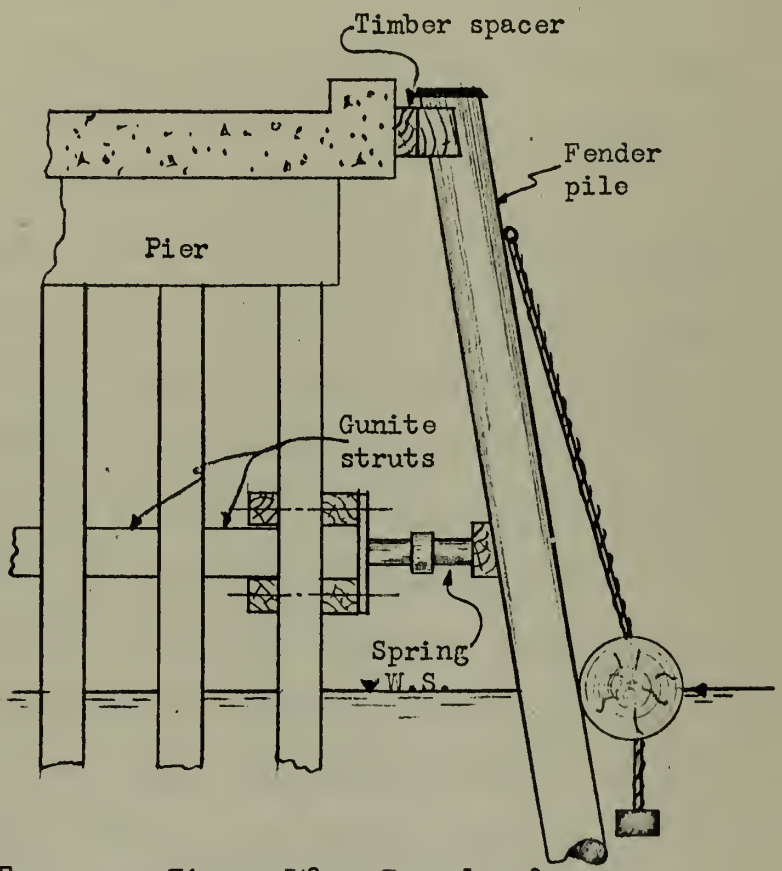


Figure 38 -- Example of a fender system using spring buffers to disadvantage

sliding cylinders becomes a little loose, the mechanism will tend to jam and result in the transmission of the impact of the ship directly to the pier or wall. Direct transfer of the shock will cause damage to either the pier or the ship. The type of installation shown in Figure 36 is somewhat more acceptable than the single wale, in that it will distribute the moment couple a little better, and will not tend to jam quite as readily. In either case, a step must be provided so that the spring cannot rebound to the extent that the casing is forced out of its housing. This can be accomplished by a chain, by through bolts to the fender, or by means of a stop within the casing itself. It is considered advisable for the spring assembly to be arranged in such a manner that the unit has a pre-set load in order to maintain concentricity of the casing and to prevent chatter of the spring during wave fluctuations.

It is very easy to overlook basic structural principles when dealing with forces overcome by fenders. Figure 38 (18) shows a design that in the author's opinion is unsatisfactory, because it fails to perform its function of keeping impact loads away from the main structure. The use of the floating camel and the rubbing strip of metal are excellent ideas, for in this way the loads are restricted to a very small section of the pile. The length of the pile from the deck to the sandy bottom was about 59' while the distance from the deck to the wale supporting the springs is only 9'-0". The springs then do two things: they absorb a portion of the energy of bending of the pile (see Chapter 3) and because they form in essence a third reaction, the pile receives a portion of the load that would normally be taken by the deck. Analyzing this arrangement leads one to the conclusion that the springs absorb some energy, but not as much as

they could if the design were rearranged to exclude the spacers at the deck level. Assuming that the pier is already loaded to some percentage of its design live load, the piles are already stressed in compression. From the drawing, as the ship strikes the fender a sizeable load is transferred directly into the piling at a distance several feet below the deck level, creating a bending moment within the piling in addition to the direct stress already applied. Add to this the small amount of additional load due to the transmitted shock, and it can be seen that bending moment due to the lateral load of the springs on the main piles could be relatively large. Next add the lateral force applied to main piles by the heads of the fender piles through the decking of the pier. Then there are these forces in the main piling to consider:vertical dead load, vertical live load, horizontal bending moment due to the force exerted by the springs, horizontal bending moment from the impact imparted by the springs, horizontal bending moment from the lateral force of the fender piles, and the bending moment due to the impact transmitted by the fender piles. Nearly all of these lateral forces could have been eliminated by the simple expedient of substituting a spring for the spacers at the deck level, and eliminating the spring assemblies at the lower level.

There are many ways that springs can be used that have not been tried before, but it is considered that the other materials such as rubber or other media such as hydraulic dash-pots will provide the same or better protection with fewer construction problems and maintenance "headaches."

VI. SUSPENDED GRAVITY FENDERS

A. Characteristics of Gravity Fenders

In designing fenders it is desired that they should be simple yet sturdy, that they require little maintenance, that the area of contact shall not be so small as to damage the ship, that they absorb energy with a gradually increasing resistance, and that they must absorb impact normal to the pier line but give away to longitudinal forces. All of these stipulations are met to some degree in the gravity or suspended fender systems. Basically, a gravity or suspended fender is a mass of concrete, steel, or other heavy material that is suspended on links, chains, or cables alongside or underneath a pier. As the ship comes into contact with the fender, it moves in an arc away from the ship towards the center of the pier and in moving it is raised. It is the raising of the mass that requires the expenditure of energy to dampen the impact of the mooring ship. Figures 39 and 40 illustrate schematically the forces required to raise the gravity fender, where the energy absorption capacity is taken as the weight of the fender times the vertical distance through which it is moved. There are other losses in this type of fender such as the energy required to initially accelerate the mass of the fender, the energy consumed in moving the mass horizontally, and the various frictional losses. These minor energy absorption conditions are usually ignored in the calculation of the fender because they are so small in relation to the whole.

B. Energy Absorption

When computing the energy absorption requirements of a fender system,

the mass of the ship is usually very large compared to the mass of the fender, so that the inertia forces of the fender may be ignored. If though, the mass of the fender is large in comparison with the mass of the ship, then the inertia forces cannot be ignored and must be figured in with the calculations. This is rarely the case. For example, where a gravity fender weighs 60 tons and the ships that will bear against it are 15,000 tons or more, there is little reason to consider the inertia effect of the fender. When this same fender is used and the mooring ship is about 400 tons, then consideration should be taken of the energy of acceleration. The effect of acceleration can be ignored if the acceleration is comparatively small.

C. Types of Gravity Fenders

Gravity fenders can be grouped into the following categories: vertical suspended, horizontal suspended, point suspended, three-point suspended, and longitudinal links. Each of these will be discussed and examples of each will be given. The use of any one of the different types will depend upon the tidal conditions, the berthing restrictions of the location, the size of the ship to be moored, and exposure to winds, waves, and currents. As an example, for large tidal ranges a heavy vertical fender would be required, such as is shown in Figure 41, with the weight depending on the energy absorption necessary.

Both Wolf(52) and Baker(5) describe a vertical fender installed on an open-water pier at Mina Al-Ahmadi on the Persian Gulf, where the fenders are hollow steel cylinders, 21'-3" long and 6' in diameter, filled with concrete, and supported by steel links or trunnions placed 17'-0" on

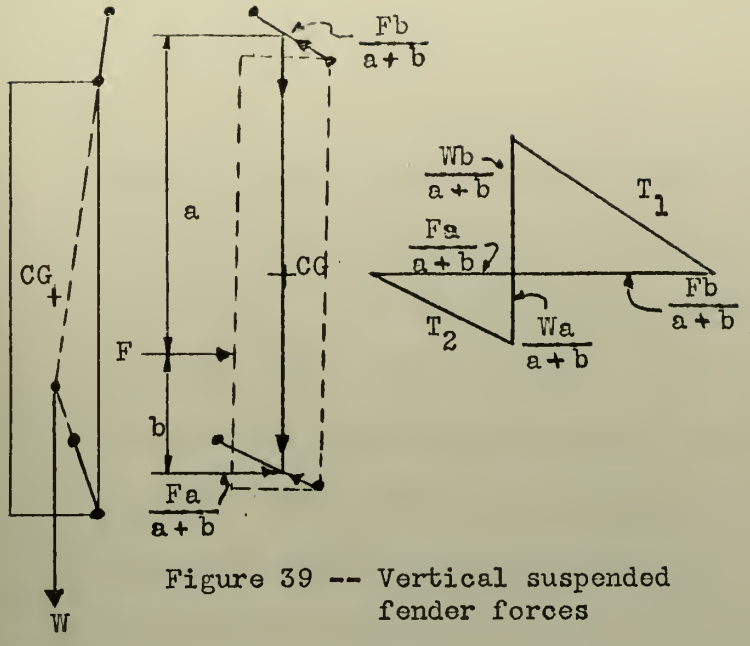
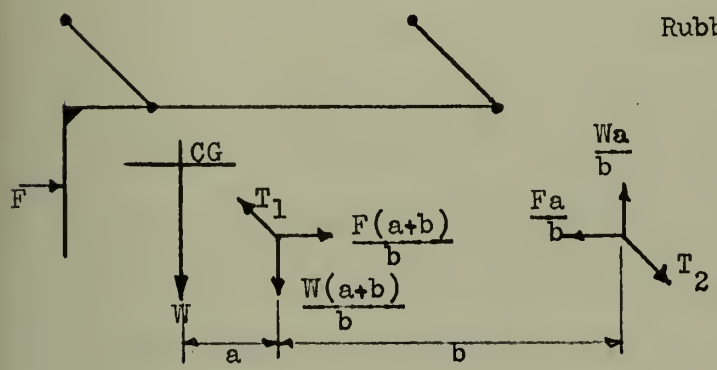


Figure 39 -- Vertical suspended fender forces



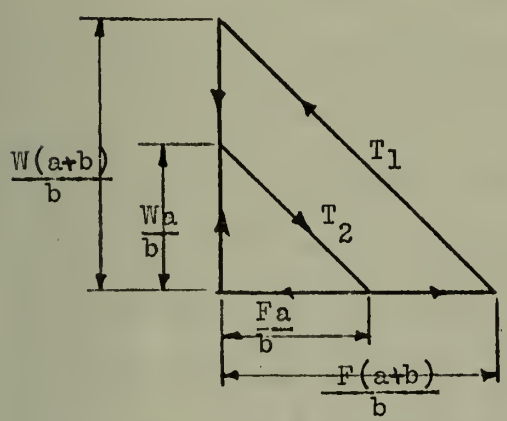


Figure 40 -- Horizontal suspended fender forces

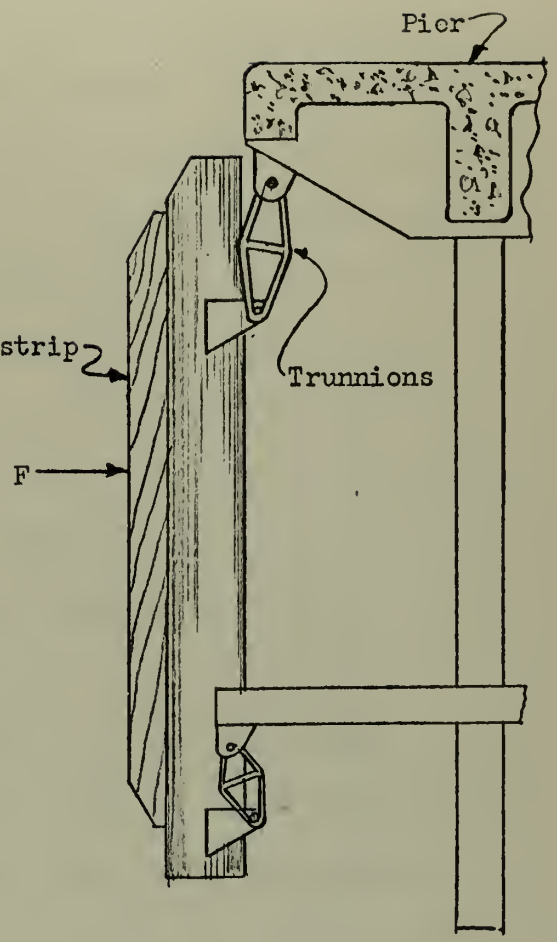


Figure 41 -- Vertical suspended gravity fender

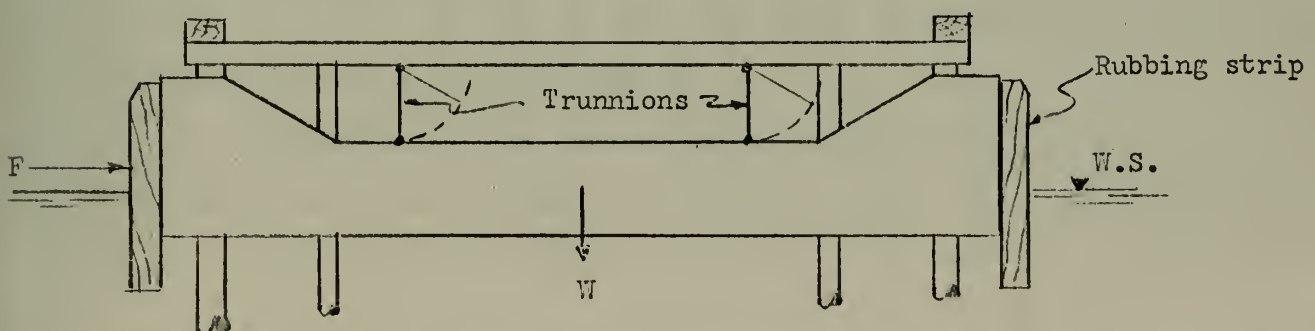


Figure 42 -- Horizontal suspended gravity fender

vertical centers. Each cylinder weighs 50 tons and is placed in groups of three at 10' on centers with the groups arranged at about 128' centers along the pier. The maximum vertical travel before the fenders are arrested is 46". Each cylinder is faced with 14" creosoted timber as chafing strips, and there are guide beams along each side of the fenders to prevent twisting due to longitudinal forces. Figure 41 is a representation of this particular installation. An important feature of the vertical type is that they can be made hollow and after erection they can be filled with concrete or sand. If sand is used, a drain can be installed at the base of the fender so that if removal is necessary at any time the sand can be easily removed and the fender can be lifted with the use of light lifting equipment. The horizontal force of the fenders can be carried to a large number of the main bents by installing a truss horizontally underneath the deck of the pier.

Professor A.L.L.Baker, the developer of the gravity fender, has shown from experiments(4) that a vertically suspended fender will give way easily when struck a glancing or longitudinal blow. In essence it rolls with the blow. Even in the case described above of Mina Al-Ahmadi the torsion beams will allow a certain amount of twisting of the cylinder to remove it from contact with the longitudinal forces. That portion of the longitudinal force that is not sloughed off will be taken by the torsion beams and transmitted directly to the main structure which will transmit the force through the deck structure to a number of the main bents.

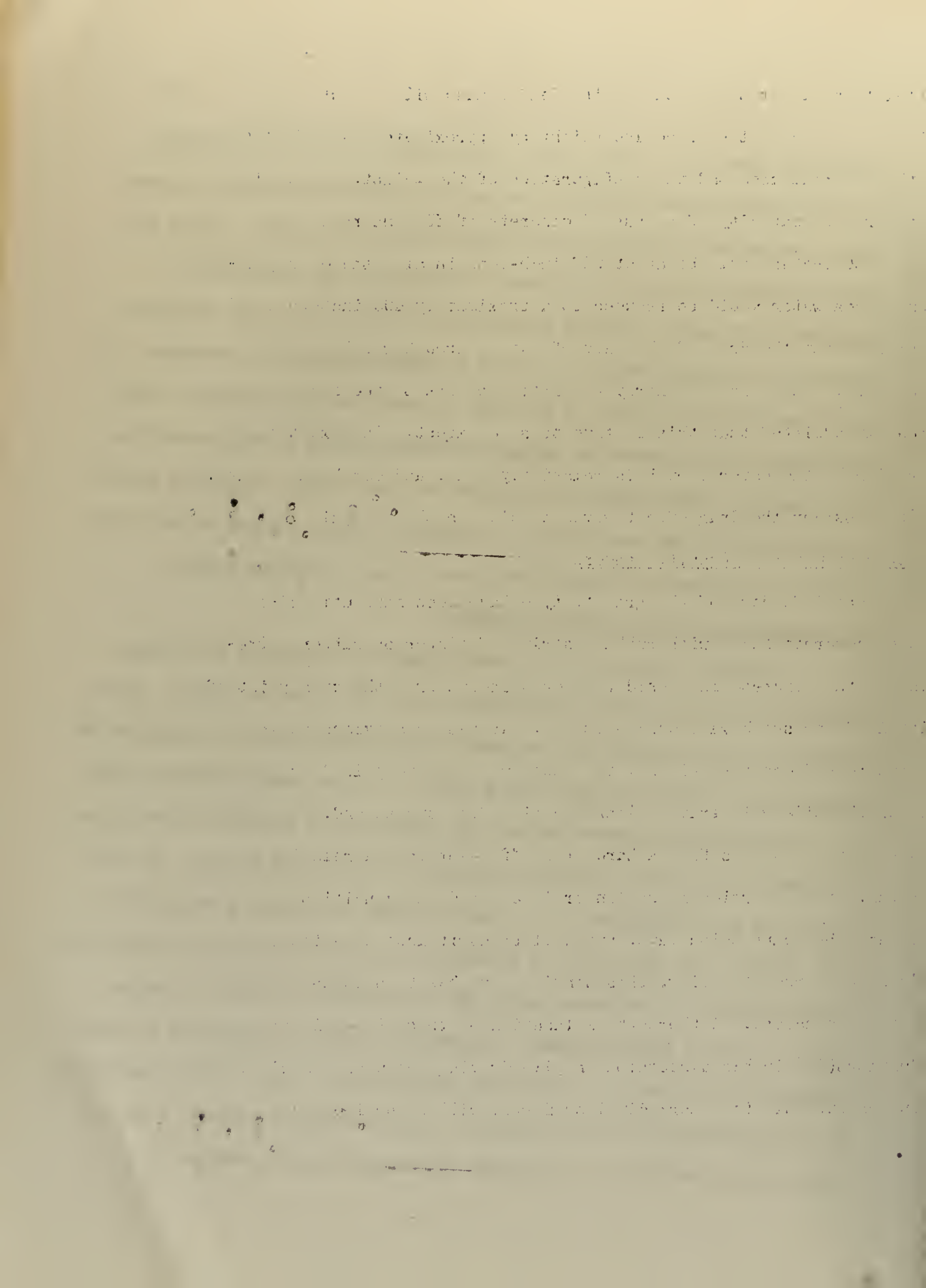
D. Reduction of Weight by Immersion

The buoyancy effect on gravity fenders when they are immersed in sea water cannot be overlooked. Whether the fender is of the vertical or

horizontal type all or almost all of the fender mass will be submerged at high tides reducing the effective weight by approximately 45%, depending on the material used and the configuration of the weight. Where the energy absorption capacity of a mass of concrete of 30 tons raised a distance of 30 inches would be about 900 inch-tons in air, the energy absorption in sea water would be reduced to approximately 495 inch-tons. It can be argued that the drag of the mass of water through which the fender must travel will increase the energy absorptive powers of the fender, and it is readily admitted that this is true to some extent. The exact amount of absorption by the water though is relatively small and can be neglected. Failure to consider the drag effect gives a value on the safe side.

E. Prestressed Concrete Gravity Fenders

Horizontal fenders of the gravity type have been made utilizing prestressed concrete faced with rubbing strips of timber or rubber. Prestressing of the concrete is considered advantageous from the standpoint of transmittal of the shock wave during impact. As has been evidenced in the use of prestressed concrete piling, the shock wave of the pile driver upon the head of the pile will travel along the pile from end to end. If the tip of the pile penetrates from a hard or stiff layer into a relatively soft stratum, the pile which is no longer in a fixed end condition will not transmit back the compression wave, but will transmit instead a tension wave. In normal precast piling, this tension wave has been known to cause failure of the concrete. A thorough explanation of this effect is provided by A.E.Cummings(12) in his discussion on pile driving formulas. A similar effect but undoubtedly to a markedly less degree will be noticed on a



gravity fender resulting from the impact blow of the ship. The shock wave will travel along the fender and because the fenders are usually free-ended the return wave will be tension rather than the original compression. A sufficient number of impacts no matter if they are small will eventually cause hairline tension cracks through which the sea water can enter the concrete and attack both the concrete and the reinforcing steel. This will lead to damage and early replacement. The use of prestressing will allow the use of a through-fender, or one that extends from one side of the pier to the other, thereby simplifying the hanging and supporting arrangements. Without use of prestressing, the fender would be much too heavy if used on piers wider than 20 to 25 feet. An example of this type of fender is illustrated in Figure 42, the dimensions of which were taken from an installation at Thames Haven, England.(33) Each fender was designed to absorb 90 foot-tons or 1080 inch-tons when completely immersed in water.

F. Examples of Gravity Fenders

Other types of horizontal gravity fenders are similar to the through-fender except they are hung on either side of the pier and are not interconnected. Many schemes have been devised and tried out with little or only a reasonable amount of success. One idea that was introduced and patented in England and based on the principle of energy absorption by lifting various weights through distances is shown in Figure 43.(42) Actually, the basic idea is very little different from the ideas incorporated in other gravity fenders, with the exception that this one will require more maintenance and result in more construction problems. It

fails in simplicity, but it does provide for an increasing rate of energy absorption. A good feature is that most of the steel is constantly below low water and the corrosion will be slight, unless micro-biological corrosion is present. Unfortunately though there are too many items of this mechanism that are prone to give trouble, and it is recommended that prior to using this particular design that consideration be given to other more efficient and more simple devices.

Nissen has designed several gravity fenders, two of which are depicted in Figure 44.(32) Patents on these fenders are held by Christiani and Nielsen, Ltd. The fender in Figure 44a is very simply made; in most cases it could be fabricated out of scrap materials around the yard. The distance the revolving wheel could travel up the rails would have to be governed rigidly for if a ship came into contact with the rail ends much damage could result. The distance of travel would be limited approximately to the radius of the large wheel minus the radius of the small wheel. A restraining device would have to be provided to prevent the fender from overtopping its lower stop in case it momentarily stuck at its upward travel long enough for the ship to move away. The frictional forces developed by the wheel sliding against the rails or in the outer wheel rubbing against the hull of the ship could be ignored for the most part as being negligible, unless additional measures were taken to increase the frictional components. This latter is not recommended because of inherent difficulties that would be encountered that would complicate the design. The fender of Figure 44b has been designed so that it will rotate with longitudinal forces, so that as the ship moves parallel to the pier or quay wall the fender will

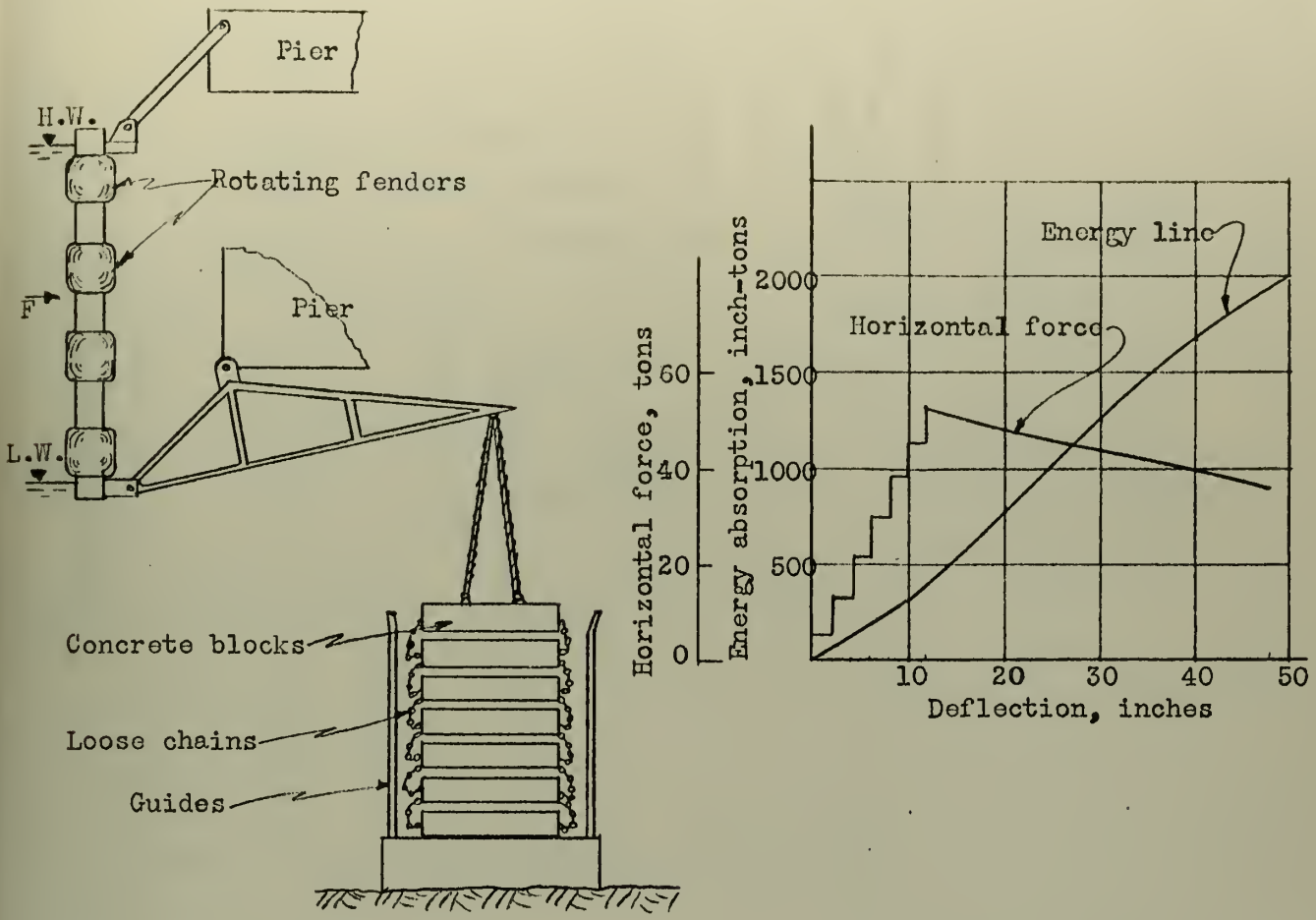


Figure 43 -- Gravity fender

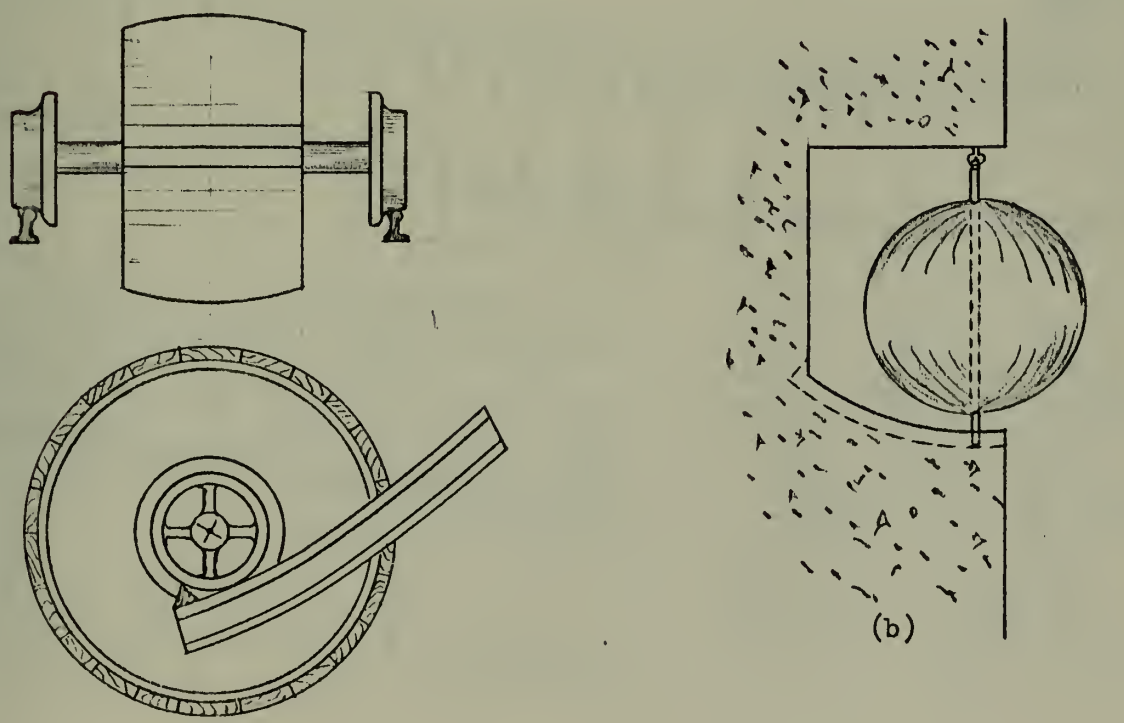


Figure 44 -- Nisson fenders incorporating gravity principles

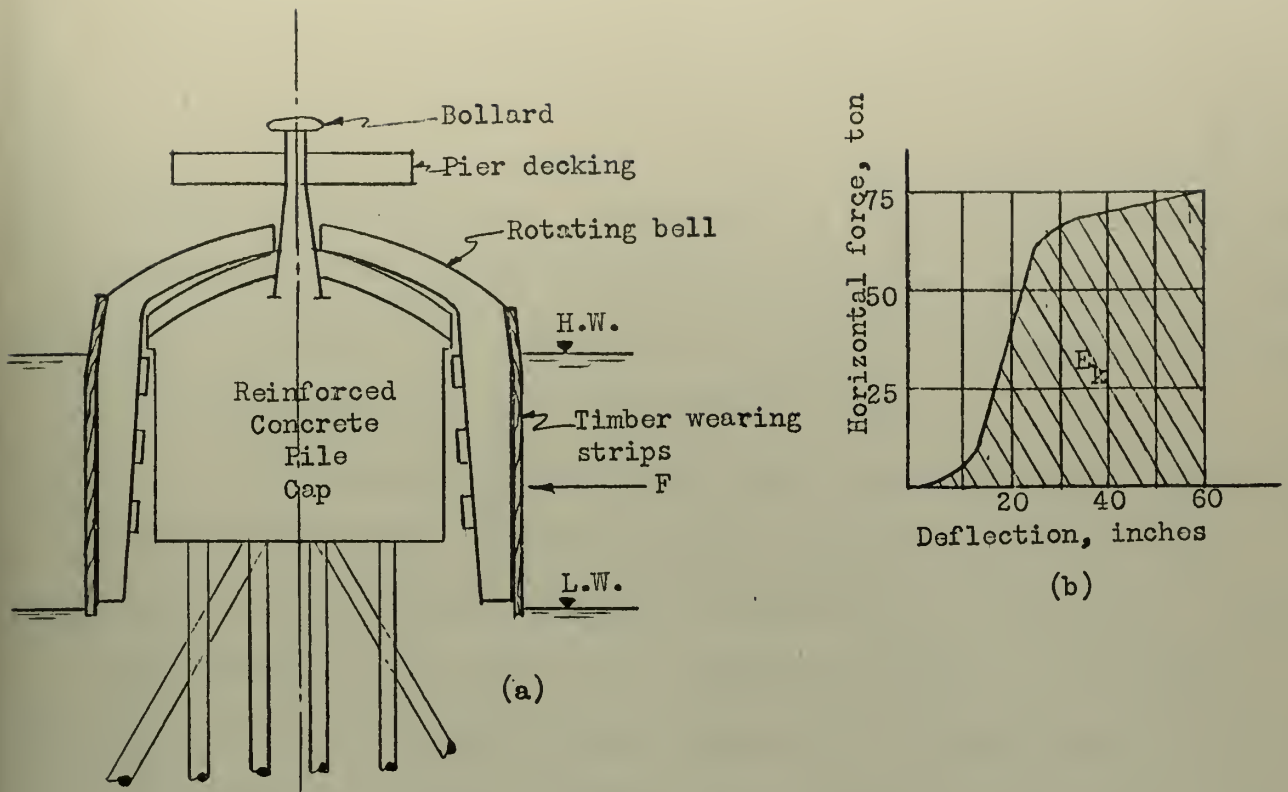


Figure 45 -- Bell Dolphin with the energy curve

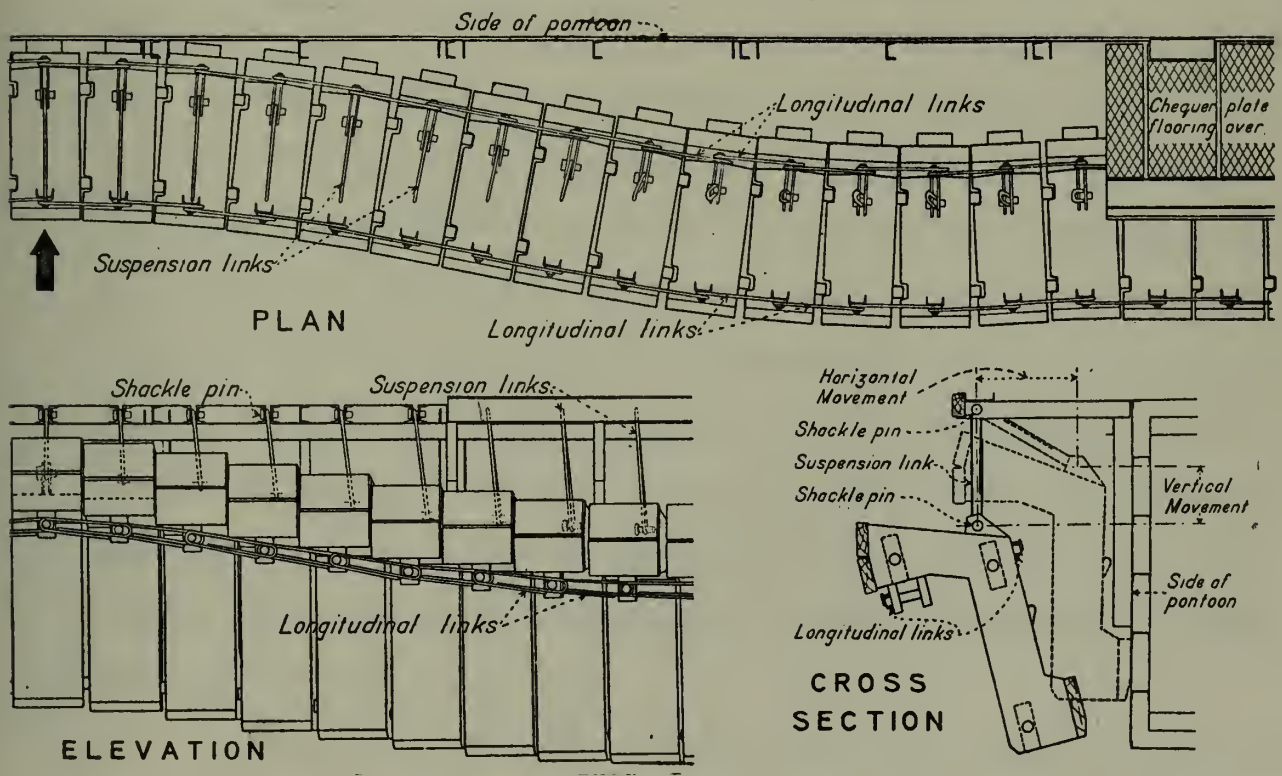


Figure 46 -- Mulberry Pierhead type gravity fender

provide no reactive forces. It is held by a tongue and groove arrangement at the base of the fender in order that only movement perpendicular to the face of the pier will be permitted. The method of suspension could become rather complicated and cause maintenance problems.

For locations where extremely large concentrated impact forces are expected from ships a suspended fender or dolphin has been developed. Known as the Bell Fender or Dolphin, Figure 45, it is essentially a large mass suspended on a central pin so that it can rotate or be deflected. Used to ward off glancing blows of large ships at exposed locations, it has proven to be fairly successful. It is limited to use in only certain circumstances where itsadded expense would be justified. Similar locations have been serviced by heavily constructed turning dolphins or enlarged pier heads. The use of one or the other will or should be dependent upon the relative costs and efficiencies for the particular locale. It is claimed that a Bell Fender weighing 200 tons will absorb as much as 300 foot-tons or 3600 inch-tons of energy, or the impact of a 20,000 ton ship at a velocity of about 1.6 knots.(5) The owners of the patent describe this fender as a "bell-shaped cap which bears on a spherical or ellipsoid surface. ...Normally the point of pivot of the bell is central, but as pressure is applied to the side, the point of pivot travels outwards, so that the resistance at the side gradually increases from zero to a force nearly equal to the weight of the bell." It can be constructed of steel, reinforced concrete, or timber.

At locations where there is little or no tidal range or on floating piers, a fairly small reinforced concrete fender such as Figure 46, and

known as the Mulberry Pierhead type, can be used. Originally used on the "Mulberry" floating harbors during the invasion of France during the last world war, they are very suitable for use on piers or quays berthing small, fast craft such as ferries. Although easy to maintain because of their comparatively light weight and small size, they have problems inherent in their use of connecting links of steel. As can be seen longitudinal links are required at three different locations on each fender to provide the necessary interaction of the individual units. Being made of steel, these links will shortly begin to corrode and will require periodic replacement if the correct action is to be expected from the fenders. Tying the units together with something other than a corrodable material will do much to increase the advantages of these fenders.

During the short period of time that gravity and suspended fenders have been in use they have proven themselves to be very good from the standpoint of simplicity, lack of maintenance, increasing rate of energy absorption, and long life. The major problems inherent with this type is the difficulty of installation and of removal for repair or replacement due to the excessive weights involved, and the manner in which they are hung. For heavy duty installations there are few of the other standard types of fenders that could perform as efficiently and effectively as the gravity types.

VII. MISCELLANEOUS TYPES OF FENDER UNITS

The foregoing chapters have described the more common types of fenders currently in use throughout the world. These are only a portion of the ones that have been or will be tried. Included in this chapter will be a number of different fenders and systems of varying designs and principles. The very fact that they have been included here as a group is not indicative that they are any less valuable or useful, but it signifies that they haven't been as thoroughly developed or as extensively used.

A. Hydraulic Fenders

Of the fender systems listed in this chapter, one is most outstanding in its future potentialities: the hydraulic buffer or dash pot. Hydraulic dampers have been used on recoil mechanisms of cannons, landing struts of aircraft, shock absorbers on automobiles, door stops, and other installations where efficient damping is required. Essentially these are all similar devices--a cylinder full of an oil or fluid so arranged that when a plunger is depressed the fluid is forced around or through the plunger head consuming energy in the process. The design is one incorporating the principles of fluid dynamics with consideration of turbulent flow in a confined pipe either through an orifice or around a constricted weir. As an added method of absorbing the energy, springs or air-pressure in conjunction with the hydraulic buffer have been utilized.

As stated earlier in this thesis, one of the requirements of a good fending device is velocity sensitivity, or the ability of the mechanism to increase the rate of application of the reactive force as the velocity

of applied force increases. The hydraulic buffer is ideal for this in that the reactive force exerted by the damper is proportional to the square of the velocity. This means that if the energy of approach is equated to the absorptive energy of the hydraulic damper, each will be proportional to the square of the velocity, and the fender will compensate for the approach velocity within most reasonable limits. This also means that the deflection of the buffer will remain constant within a relatively narrow range, regardless of the velocity of the impinging ship.

The mass sensitivity of the hydraulic damper is relative to the position the plunger or deflection of the buffer. At the beginning of the deflection there is little or no mass sensitivity, but as the damper is depressed the mass sensitivity rapidly increases until it becomes very strong at the lower velocities. Within certain ranges this mass sensitivity is not as important a consideration as the velocity sensitivity, for it means that the ship will receive the same unit reactive force at the beginning of impact regardless of the size or mass. The buffer is usually so designed that the reactive force at impact is relatively small and as the reactive force increases, the velocity decreases; the sensitivity of the buffer to mass is increased. Therefore, because the hydraulic damper is designed to rapidly increase the rate of energy absorption as the unit deflects, the mass sensitivity is more important at the later regions of travel.

A great amount of research on shock absorption by hydraulic buffers has been done by both the automotive and aircraft industries. The buffers used as fenders are very similar to those used on airplanes. Both use the principle of a compressed air cushion that will give an initial reactive

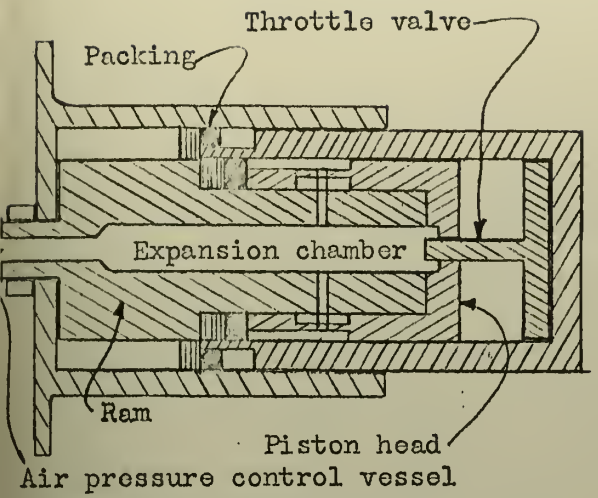


Figure 47 -- Hydraulic buffer unit using external air supply

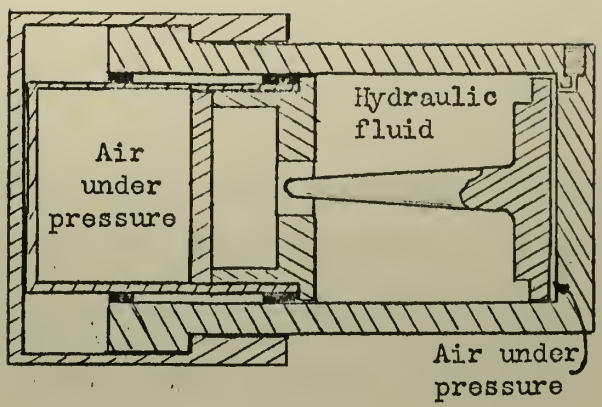


Figure 48 -- Hydraulic buffer unit using internal air supply

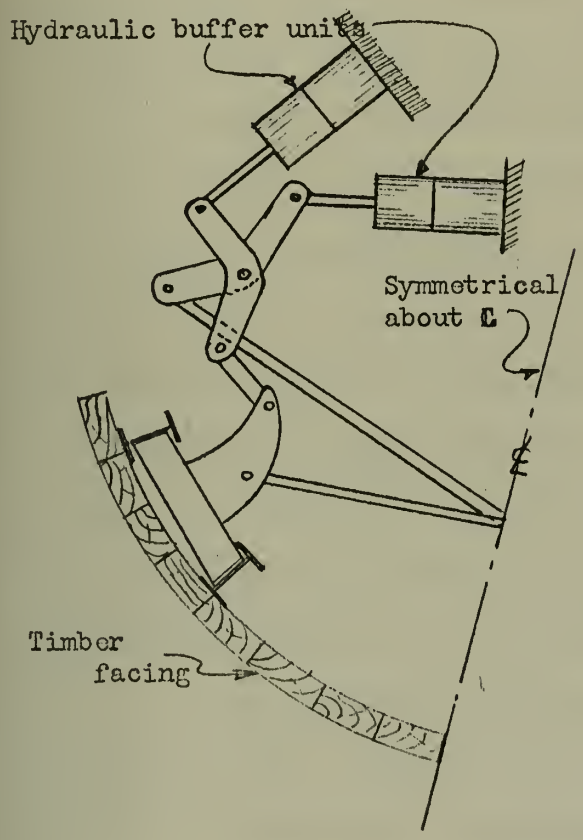


Figure 49 -- Hydraulic buffer installation

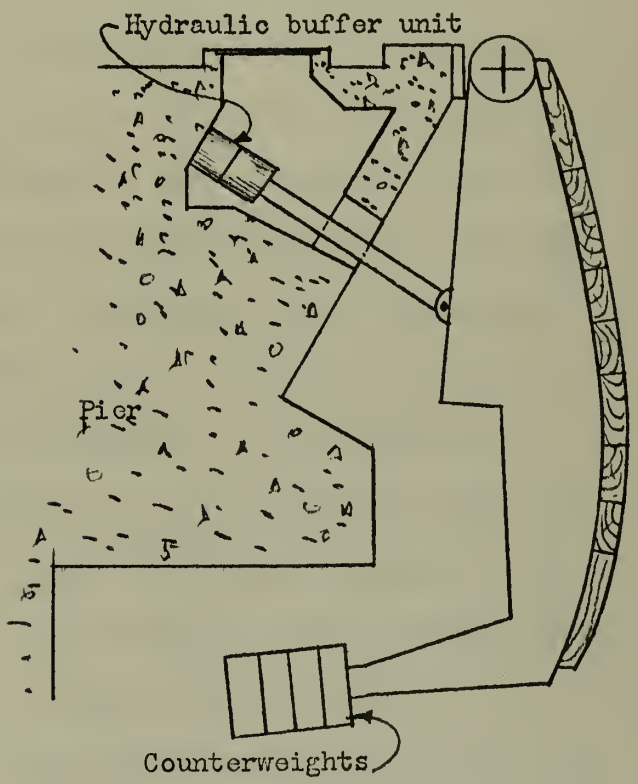


Figure 50 -- Hydraulic buffer used with a gravity fender

load and will cause the buffer to return to its original position as soon as the load is removed. A representative hydraulic buffer(50) is shown in Figure 47 incorporating an external air-pressure supply, while Figure 48 is a buffer using an internal air pocket under pressure. The action will be similar, with the exception that the internal air pocket pressure will increase approximately as the inverse ratios of the volumes after Boyle's Law, while the buffer with the external air supply will maintain a fairly constant air pressure. The desirability of one over the other will reflect the requirements of the individual location, circumstances, and designer. The buffers shown in Figure 48 can be designed so that at low velocities (0.5 feet per second) the hydraulic energy absorption will be about 80 inch-tons and the pneumatic absorption will be 80 inch-tons or a total of 160 inch-tons for a deflection of 12 inches. At a higher velocity though the energy absorbed hydraulically will be equal to 80 inch-tons times the square of the quotient of the new velocity divided by 0.5 feet per second. Therefore if the new velocity is 2 feet per second, the new hydraulic absorption will be 1280 inch-tons. The pneumatic absorption will remain at 80 inch-tons for a total of 1360 inch-tons.

The problem of using hydraulic buffers has more ramifications than with a buffer using springs or rubber, for there is the question of leakage of air-pressure, the leakage of the hydraulic fluid around the packing, and the need for higher quality workmanship on the individual units. Although they can be used in the same manner as spring or rubber buffers, this arrangement would be far more expensive and would be a wasteful use of units because they are so much more efficient in energy absorption.

Consequently, hydraulic buffers have been used in mechanism where their high energy absorption capacities can be fully utilized. Figure 49 shows the method of installation at the Ferry Terminal, Dover, England.(50) These are arranged so that all four buffers come into action regardless of what angle the ship strikes the fender. Figure 40 is a method described by Du-Plat-Taylor(13) in use at the Mole du Verdon, Bordeaux, France. Four of these fenders acting together will absorb the impact of a 60,000 ton ship travelling at a velocity of 1.0 foot per second. Spaced at 49'-0" on centers and weighing 32 tons each, a considerable portion of the kinetic energy is absorbed by raising the weight through a vertical distance, while the remainder of the energy is absorbed by the hydraulic dash-pot.

The problems inherent with either of the two above mentioned examples are not numerous but they are sizeable. The system at Dover is fairly complicated and without proper adjustment could give endless maintenance problems. The problem of the second, at Bordeaux is the same as with any gravity fender: weight. A large crane is necessary for removal of the individual fender whenever work is required. It is obvious of course that for the latter only large ships can be berthed at these fenders. Small vessels, berthing at high velocities would be subjected to too great a unit pressure on their hulls. It might be well to add that this installation is located where only the very large, ocean-going vessels are berthed.

B. Floating Fenders:

One of the most simple of the fenders is the floating device. Originally the camel log was used as a fending device, although it is now realized that it causes higher stresses to be placed in the main piles of

the pier than if it were eliminated. When properly used camels are employed only as spacers, and are kept away from those locations where vessels are liable to come into contact with them first when mooring and thereby transmit all of the mooring impact directly into the main piles at water level. Several interesting devices have been used by engineers employing the floating principle; by having the fender float, you strike the ship at the water line or at any predetermined point so that there is a rolling moment set up that will decrease the stresses applied by the initial impact.

A system described by Minikin(27) and used on the quays at Tyne Harbor is depicted in Figure 51. Held in place by a weighted chain it rises or falls with the tide remaining at water level. Shock absorption is obtained by means of the rubber washers acting in compression between the two wooden laminated wales. This system is feasible only on quay walls or moles; to be used on open piers, wales would have to span the entire distance between the main piling. A similar type of fender, shown in Figure 52, is used at Nilsson-Hiort.(36)

An interesting floating fender incorporating the principles of the gravity system is used at the New Wharf, Port of Tiko(31) and is illustrated in Figure 53. The fender itself is a floating chamber with timber rubbing strips that transmit the impact of the ship directly to the weight hung underneath the deck of the pier or wharf. The energy is then absorbed by raising the weight through a vertical distance. The method of repair of this fender makes it desirable from a maintenance engineer's standpoint. Should something happen to the fender so it needs maintenance, or should

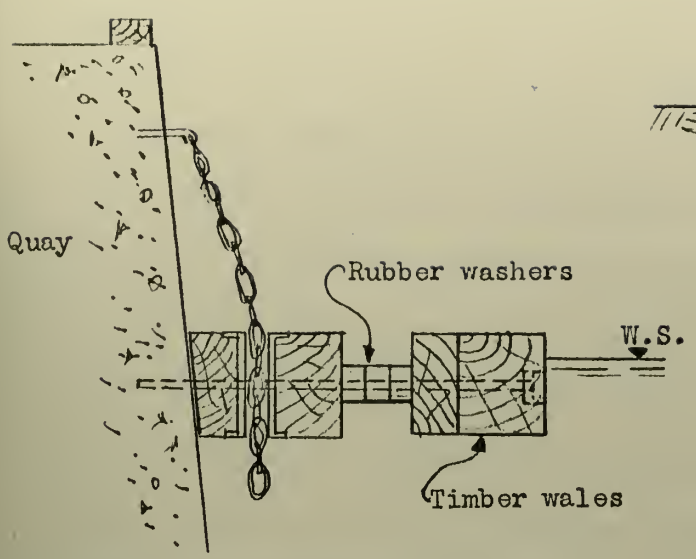


Figure 51 -- Floating fender for use on quay walls

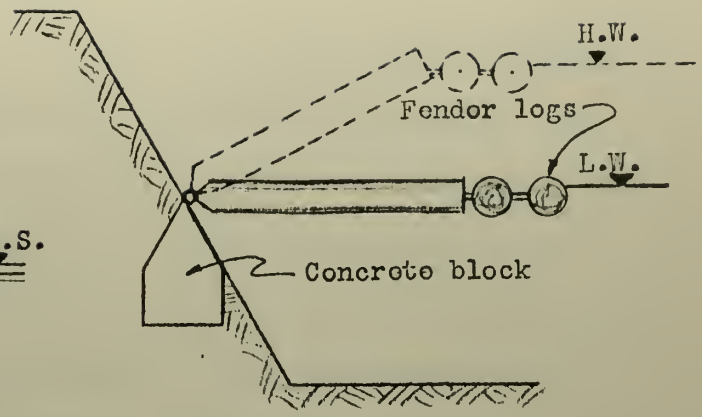


Figure 52 -- Floating fender

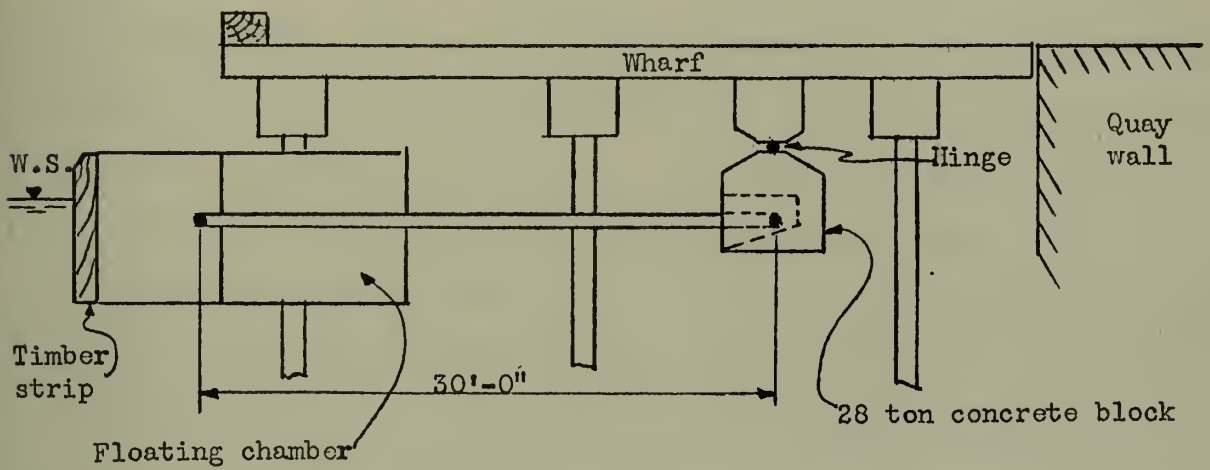


Figure 53 -- Detachable floating fender

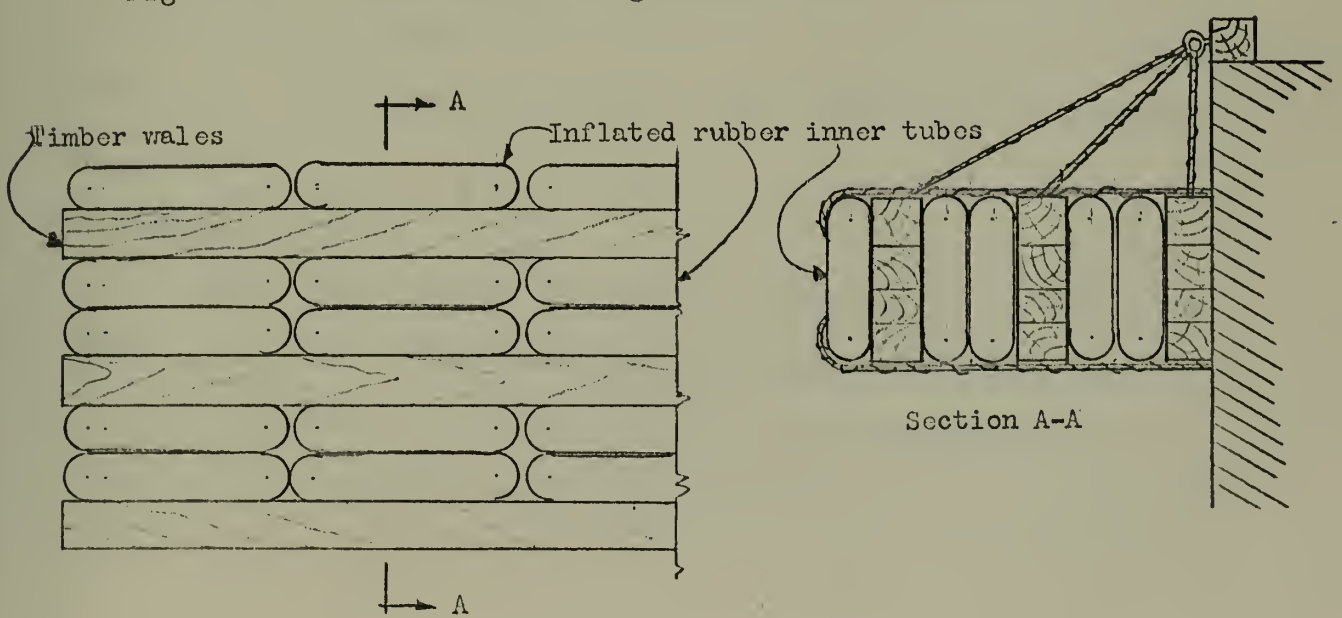


Figure 54 -- Tweddell floating fender or catamaran

it require painting, it is easy to get under the deck by boat, disconnect the floating section from the weight and then float out the fender. In order to facilitate rapidity in turn-around, an additional floating fender is provided and can replace the damaged one immediately with no lost berthing time. This particular fender has a counter]weight weighing 24.8 tons in air. In practice, the counter-weight can be so designed that it will remain in air all of the time increasing the weight efficiency of the system, and reducing the unit cost of energy absorption.

A new design of a floating fender that has received notice over the past several years was designed by Captain A. J. Tweddell in England, and actually can be made of materials that are found in almost any yard. As shown in Figure 54 each section weighs about 10 tons. Originally 6'-4" wide, it is compressed by means of cables or bolts to 5'-10" to give it an initial set. As designed it is claimed to be able to handle impacts from ships up to 29,000 tons. Similar floating fenders or "catamarans" are described by J. H. Jellett(21) for use when docking the liner, the United States. The author's main objection to such a fender is its bulkiness and unmanageability. Jellet describes his fender as being 10'-0" deep instead of the 6'-4" of Tweddell's, which makes it even more bulky and unwieldy.

C. Pneumatic Fenders

Fenders incorporating the use of air under pressure have not been used to any extent, nor have they been developed to the point where they are really efficient. Of course, the use of air in conjunction with hydraulic buffers utilizes air pressure, but these units are basically of

another type. A very common method of using air-pressure is to utilize ole rubber automotive inner tubes inflated and hung alongside the pier or quay wall. Actually, Tweddell's fender described above makes use of this idea. Andri(2) suggests the use of rubber truck or airplane tires filled with foam rubber with the rim opening of the tire covered and made air-tight. One or more release valves are installed in the casing of the tire so that as the vessel comes into contact with it the air is expelled under pressure. After the impact has been absorbed and the ship moves away, the foam rubber will expand and draw air into the casing through a reverse-acting valve. For use in areas where the impact stresses will be small or when dealing with small craft, this method could serve very well, but it is the author's opinion that there are many other fending devices that will perform better with less susceptibility to damage. The air-intake and release valve would undoubtedly be a source of maintenance problems.

D. Hung Fenders

Even though they are not a separate type of fender by themselves, at least not as discussed by this report, it is considered proper to mention the hung fender. A hung fender is one that is attached directly to the pier or quay and does not come into contact with the underlying soil. A hung fender can be of a rigid type that is nothing more than a grill work of rubbing strips set vertically and horizontally on the face of the quay wall, or it can be a vertical fender of timber that may or may not have a buffer mechanism between it and the pier. Therefore, instead of the lower end of the fender transferring the impact loads

directly into the soil, it is either hinged to the pier or it is held by buffers both top and bottom. On piers where very deep waters are encountered, it is inadvisable to make use of long fender piles because of the accompanying large deflections under loads, and because of their susceptibility to damage. Therefore, it is advisable to use hung fenders whenever the depth of water exceeds approximately 40 feet. This correctness of the figure of 40 feet can be argued and has been varied as much as 15 feet either way. It is up to the discretion of the designer and limited by the factors of the locale. The 40 feet figure is a norm. It is well to remember that when hung fenders are used that a lower support must be provided. This support is almost always below low water, and can give a great amount of maintenance trouble in addition to the problem of installing the initial bracing. Hung fenders are becoming increasingly popular with harbor engineers and are being used in locations where fender piles or some other type of fender could be more economically and efficiently utilized. It has the advantage of ease of maintenance when and if there is damage to an individual fender. They are light enough that they can be removed with only the lightest of lifting gear, and they can be repaired by one or two men within a very short time. The ease of maintenance when figured in the over-all cost could easily be the deciding factor in the final decision as to the type to construct.

E. Branches, Rope, Cork and Rubber Tires

No thesis on fenders would be complete without a discussion of the use of branches, rope, cork, and rubber tires. Because of the extreme shortage of timber and other fendering materials during World War II,

the harbor engineers were forced to retreat to the use of the old methods. In fact, since that time there have been several harbor masters who swear by these methods preferring them to the more modern approaches. In the section on fenders and dolphins in the 1953 Congress of the Permanent International Association of Navigational Congresses held at Rome, several of the papers presented designs utilizing timber branches wrapped around cylindrical steel tubes and tied with cable or wire. The resilience of these fenders are much greater than is realized from a cursory examination; in addition, they are very inexpensive, and will last with little or minor maintenance for a period of from three to five years. Hung directly against the quay wall for contact with the side of the ship, or used as a buffer as one would use rubber or springs, they have performed satisfactorily. In direct contact they will accept only those loads which are normal to the quay wall, and will roll with the longitudinal forces. Of course, the energy absorptive qualities are limited, but if this is understood by both the engineer and the ship handler, then they can be used when other materials are not available. At Bremerhaven, Germany, these are used on the Columbus quay with each handle having a length of about 19 feet and a diameter of approximately 7 feet, made with a core of thick heavy branches, and an outer layer of smaller, thinner branches of wood.

Making rope fenders is one of the age-old occupations of the sailor during the long voyages and they are still used extensively on small craft. Remember the bow fender on the small tug boats? But the rope fender is giving way to the rope and cork or rope and rubber tire fender.

Here a piece of cork or an old truck tire is wrapped firmly with manila line with a surprising resiliency resulting. A number of designers use cork and rope fenders as buffers between the head of the fender pile and the pier to help absorb the impact. The coefficient of restitution is small, which is a mark in its favor. Actual values of energy absorption are difficult to give for these fenders for so much will depend upon the method of construction, the workmanship, and the materials used.

F. No Fenders

In many harbors, and some where large ships berth, the use of resilient fenders is thought to be an unnecessary consideration for the ship owner. Here are used solid blocks of timber, either cylindrical or square, that are installed at the water surface and held in place by chains or are allowed to slide up and down on a single standing pile. When an engineer was questioned regarding his reason for using such a system instead of resilient fenders, the author was told that it is up to the ship handlers to worry about the impact. The quay wall was more than sturdy enough to take any impact, so if the skipper was foolish enough to come into the berth at a high velocity, then he would be responsible for the damage to his ship himself. This is the incorrect attitude to take. It is the author's opinion that the harbor engineer is responsible not only for serving the owner of the pier or wharf, but is also responsible that the ship is not damaged during normal berthing. It is well to remember that it is not always in the best interests of the pier owner to make it difficult for the ship owners; they can always carry cargo for others.

VIII. REQUIREMENTS, RECOMMENDATIONS, AND SPACING

A. Questions

The questions that the designer of a pier must answer every time he is working on a new structure are: If I provide fenders, what kind and how big must they be? How must I arrange them? What size ships will use the pier? What size ships will use the pier twenty years from now? How much can I spend on fenders? What should the life expectancy of fenders be? These and many other questions apply in essence not only to fenders but to the entire structure or to any structure. We are now interested in only that portion of the problem that deals with fenders.

Fortunately for the designer when he starts work on a new pier or wharf he is fairly certain of the size and the weight characteristics of the ships that will use the facility, at least for the five or so years after the structure is completed. As soon as the structure is located, the effects of the exposure conditions can be readily determined. With the exposure conditions, the size and weight of the ships, cargos to be carried, and the physical characteristics of the area known, the impact forces to be expected and how they will be carried to the soil and absorbed can be determined. The type of structure will be a determining factor on the selection of the fender, for only certain types of fenders can be used with each particular pier or quay wall. Actually, the designer must either select the main structure and design the fender for the structure, or design the fender and select a structure to fit it. This latter is very unusual, so it will be assumed that the fender must be such as can be efficiently used on the main structure.

B. Recommendations

Table VIII is a compilation of the major types of different mooring and berthing structures under varying conditions giving the types of fenders that are suitable for use. The author hastens to add that this is not meant to be a firm, but only a general recommendation, for in each case the individual factors must be considered separately. Where Table VIII may show fender piles as a method of fendering, an examination of the site may prove that the underlying soil is of such poor quality that piles would not be satisfactory. In another location gravity fenders may be listed, but unless the means of lifting the heavy weights is available at the harbor, the expense in the future for crane service might prove to be unwarranted.

C. Requirements

Briefly, there is set forth below some of the major requirements of the various types of fenders:

1. Fender piles

a. A firm bottom into which to drive piles.

b. The main structure should be protected by a buffer between the head of the pile and the pier, or the main piling must be designed to accept the impact loads.

c. These fenders can be used on almost any type of structure where space is not a deterrent, or where the depth of water is 40 feet or less.

d. Facilities for driving piling should be available at the site, for there will be a number of replacements necessary periodically.

e. The availability of replacement piles and buffers should be

Table VIII

RECOMMENDED FENDER SYSTEMS FOR DIFFERENT TYPES OF BERTHING STRUCTURES

Berthing structure	Fender Pile				Gravity or suspended	Rubber tubing	Special fender design	Floating fender	Timber waling with buffers
	Spacer block	Rubber buffer	Spring buffer	Hydraulic buffer					
Quay wall		X	X	X		X			X
Timber wharf		X			X			X	
Concrete wharf		X		X	X			X	
Mole or solid pier		X	X	X		X			X
Timber pier		X							
Concrete pier		X		X	X			X	
Composite pier		X						X	
Floating pier or landing stage							X		X

* It is considered that the ships using the structure will be of a size requiring fenders.

considered at locations where other materials are easier to procure.

2. Rubber buffers

a. The use of rubber, particularly that which comes in tubing, will require a fairly solid backing against which it can transmit its loads.

b. If properly designed these rubber buffers, whether in shear or compression, should not transmit more than 10% of the impact to the main structure. It is normal to design for no more than 45 degrees movement in shear and no more than 50% deflection in compression.

c. Rubber buffers can be used on almost any type of pier structure, with the exception of the rubber tubing, which will require a continuous backing.

d. Rubber is very easy to replace because of its light weight and ease of handling. If ready-made units are available, there is no need for any special repair equipment. It is necessary though to maintain a constant surveilance on the rubber units to ascertain their deterioration or failure.

e. Rubber units should be stored in anticipation of future replacement needs; therefore proper storage facilities are necessary.

3. Spring buffers

a. As with rubber, the spring buffer requires a solid backing on the pier or quay wall.

b. Springs will transmit only a small portion of the impact load, but consideration should be given to the possibility of having one or more of the spring assemblies jamming and thereby throwing the entire impact load directly into the main structure. It is accepted practice to design spring units so that the spring is never stressed beyond the elastic limit,

and for normal usage an acceptable safety factor of from 1.5 to 2.0 should be used depending upon whether it is based on the elastic limit or on the ultimate strength.

c. Spring buffers can be used on almost any type of waterfront structure. Probably the biggest problem with the use of springs is planning for replacement in the future years. Experience in the past has shown that the design of the individual units change periodically so that when repair or replacement is required, the original design is no longer obtainable. The system then will have to be rebuilt, or the spring will have to be made as a special job necessitating additional cost and a comparatively long repair time.

d. Repairs to the spring assemblies, although not the job of a specialist, do require special equipment. Especial care must be exercised in the repair or servicing of spring assemblies because of their propensity for jamming.

4. Suspended gravity fenders

a. The weight of the fender is limited to the load carrying capacity of the supporting piling.

b. At the farther end of travel of the gravity fender, there are considerable lateral forces that must be carried by the main piling. For main piling of great length, this could be a sizable factor in design, requiring a material increase in the size of the structural shape to be used. As mentioned previously, this lateral force can be carried by separate piling, or can be distributed to the main structure by means of a horizontal truss tied to the deck of the pier.

c. Gravity fenders are best used on open structures, although by building a supporting framework they can be used on quays and moles.(5) When the pier is wide or where a wharf is used, a fender serving only one side of the structure is recommended, but for a narrow pier a through-type fender would give the best results. Where it is desired to permit the fender to refuse to take longitudinal loads, gravity fenders will perform very well.

d. One of the biggest factors influencing the selection of gravity fenders is their weight. Heavy-duty lifting equipment is required to repair and maintain them. The vertical fender that is hollow and filled with sand and the floating fender are two of the answers to this problem. There is a possibility that the gravity fender may be affected by the wave forces, providing the waves are of the same period as the natural pendulum frequency of the fender. It is conceivable then that the fender will start to swing in increasing arcs until damage will result.

e. Replacement materials or parts for gravity fenders pose no problems. Any yard can fabricate its own replacement parts very easily from concrete. If one fender becomes damaged or broken, it is only a problem of setting up a form and pouring another fender. After the proper curing period it can be slung into place.

5. Hydraulic fenders

a. Hydraulic dampers have basically the same structural requirements as do spring and rubber buffers.

b. Proponents of the hydraulic buffer claim that the shock energy

transmitted to the main structure is only a small percentage of what is transmitted by the other standard fender systems. Needless to say, the proponents of the other systems make similar statements about their fenders. It would seem though that the amount of transmitted impact energy would be a little less in the case of the hydraulic buffer or damper.

c. The hydraulic damper is not restricted to any particular type of pier or quay, but with the proper arrangement can be used on any berthing structure.

d. A well-equipped shop to maintain, service, and repair hydraulic units would be necessary. Fairly close tolerances would be required in this work, therefore the man detailed to the maintenance of the units would have to be skilled.

e. It is with the hydraulic damper that the availability of materials and parts would be most critical in the future years, say ten to fifteen years after the installation was originally made. At the present time hydraulic fenders are rare and there is no ready market for them, so that the manufacturers make them only under a special order. Therefore, when additional units need to be constructed, new dies and templates would be required at a large expense and the loss of a great deal of time.

The foregoing is only a sketchy list of requirements for fenders, for a really comprehensive listing would necessitate consideration of each different type of structure with an accompanying discussion on the relative merits of each system. The list will give an indication of the problems inherent in the design of the fenders. There are many objections

to the different types of fendering and most of them are justified. In selecting a system it is the best procedure to find that fender system which will meet the requirements with the least number of objectionable features, and will fall within the cost estimates established for the job.

D. Spacing

In order to take the impact of the ships, the fenders must not only be adequately designed individually, but must be spaced so that at any reasonable angle of approach of the vessel a numberof the fenders will be acting. The length and shape of the side of the ship will be of importance in the considerations. At those areas where only a short length of the ship is anticipated to act, but where the entire impact may be centered, the fenders must be closely spaced. Where it is anticipated that a large segment of the vessel's side will contact the fenders, the fenders may be spaced a consistent distance apart. This is a matter again of economics; the cost of the individual fenders of varying sizes must be equated against the spacing required of each capacity. The most economical should be used.

Assume that a ship to be moored will have a nominal impact energy of 400 inch-tons and it can be expected that the vessel will contact 150 feet of the pier at the initial contact. It is a matter of economic decision whether to use five fenders spaced at 30 feet each and capable of taking 80 inch-tons each, or to use three fenders spaced at 50 feet capable of taking 133 inch-tons each (notice that the spacing gives the least favorable condition; at 30 feet it is possible to have six fenders acting). The contact area of each fender and the accompanying unit force that will

be impressed on the hull plates of the ship should be considered also. This factor may limit the fenders to a minimum number.

If the angle of approach of the vessel, that is the angle between the longitudinal axis of the ship and the longitudinal axis of the pier, is large the under-way component of velocity of the ship will be transmitted into the fender system in an amount proportional to the sine of the approach angle. This is a problem that must be answered by each designer. If it is possible to ascertain the general location of this impact, a closer spacing of the fenders can be accomplished, or additional protection of the pier can be obtained by means of strengthening the piling. It should be remembered that when a ship strikes a pier with a bow-on approach, or large approach angle, the moment couple created about the center of gravity of the ship tends to swing the ship horizontally toward the pier reducing to a large extent the imparted kinetic energy. When the decision is reached as to the amount of impact energy to be expected, then it is a matter of spacing of the fenders.

Spacing is a function of the kinetic energy, of the approach angle of the ship, the configuration of the pier or quay, the shape of the side of the vessel, the length of the ship, the capacity of the individual fender, and the unit stresses allowed on the hull of the ship. The practice of some engineers of using a standard spacing is open to some censure, but if the spacing is close enough it will be safe. although normally more expensive than necessary. Unfortunately, the engineer is limited mostly by the maximum permissible spacing, because he must consider not only the largest vessel to be using the mooring facility, but also the

smallest craft that will be regularly using the pier. The smallest craft should have at least two fenders against which it can berth, otherwise the mooring and the approach will be very unstable.

The Department of Marine and Aviation of New York City has used a method of fender support that is interesting and very advantageous for isolating the impact loads from the main structure. They drive a system of piling separate from the main piling and to this separate system they attach the fenders. The fenders take the total kinetic energy of the mooring vessel and transmit it to the piles which in turn transmit the forces to the underlying soil. The main structure is untouched except when an extremely heavy impact is encountered and the fender system has deflected to its limit. Where a large number of craft that cannot be easily controlled such as barges are being docked, this method has many advantages that standard fender designs do not have.

The size of the fender should be commensurate with the size or mass of the using ship. It is ridiculour to assume that small, light-weight buffers would be used for a large, ocean-going tanker of 40,000 tons, or that 40 ton gravity fenders would be utilized for small inland-coastal waterways traffic of perhaps 500 tons. Although some engineers recommend the use of a standard impact energy of 400 inch-tons the factor of mass-sensitivity must still be considered in the selection of a fender. It will be found that for the larger ships, the larger the mass of the fender the better will be the energy absorption; the limits of design will be a matter of experience and engineering judgment.

IX. COST, CONSTRUCTION, OPERATION, AND MAINTENANCE

A. Costs

In the past attempts have been made by various engineers to set forth unit costs of fenders. As in any such undertaking, these figures are limited in value because of the restrictions set upon the method of computation. It is the opinion of the author that to be of use the cost data should be broken down into several different categories, i.e., cost per unit of energy absorption capacity, cost per square foot of pier or wharf area, cost per individual fender unit, and cost per linear foot of pier.

D. M. Little(24) has published some general cost figures that he has derived from actual construction in his experience. These figures are broken down in Table IX.

Table IX

Fender type	Cost/100 inch-tons	Cost/linear foot of pier
✱ Steel fender piles	$1400. to $2800.	$140. to $280.
✱ Concrete fender piles	$1400. to $2800.	$140. to $280.
✱ Fender piles w/rubber buffers	$1540. to $3080.	$154. to $308.
⊕ Concrete gravity fenders	$560.	$140.
✱ Timber fender piles	$1400.	$140.

✱ Based on the fender piles being spaced at 10'-0" on centers.
⊕ Based on one gravity fender every 15 feet.

It can be seen that the cost per linear foot of pier is very close to being equal for all cases. Because of the necessity of keeping the spacing of the fenders relatively small the gravity system is capable of taking three times as much energy absorption as the others. The cost of the fender piles is based on a capacity of 10 inch-tons per linear foot of pier while the gravity fenders are capable of taking 30 inch-tons per linear foot. If the berthing ships are such that the gravity fenders can be spaced at 30 feet instead of 15 feet, then the cost per linear foot will be reduced to about $70., or one-half of the capacities of the others, and will still have the absorption capacity of 15 inch-tons per linear foot. As an example, the large fenders at the Mole du Verdon, Bordeaux, France, are spaced at 49 feet on centers. Spacing the gravity fenders at 45 feet on centers will reduce the energy absorption ability to the standard 10 inch-tons per linear foot and the cost to about $47. per linear foot of pier.

Cuerel,(11) in a discussion of Little's figures,has recommended that the cost for gravity fenders be increased by about 100% to bring them into line with the increase in unit prices over the years. This would also take care of piling work required in addition to that which would be used on a comparable fender pile system. Referring to the above paragraph then, the unit costs as indicated by the study of Little would be approximately doubled. Cuerel also finds a divergence in his own construction experience with the erection costs of fender piles of timber with rubber buffers, where they cost only $590. for each 100 inch-tons of absorption capacity. From these comparisons it can be seen that the range of costs is great,

for both were taken from actual construction contracts. Cuerel explains a portion of this by stating that the unit costs of materials have varied greatly since the compliation by Little, where as an illustration, rubber has decreased in price to 40% of its original cost. This discussion serves to re-establish an axiom of estimating that engineering estimators have been aware of for years: prices of materials are subject to great fluctuations and must be re-studied prior to estimating and bidding each job. To attempt to establish set ratios between costs of the various types of fender construction would serve the purpose for only the time when they were ascertained. Within a matter of six months the changing unit cost picture could vary the total prices by as much as 50%.

It is evident from a study of the recent engineering literature that fendering is fast becoming a bigger and bigger problem in the design of berthing facilities. The cost is growing to proportions that involve a considerable percentage of the cost of the over-all structure, and can not be ignored. With the advent of ships of upwards to 80,000 and more tons, the engineer must consider the effect of the impact on the piers and quays. With ships of this tremendous size, the figure of a 400 inch-ton impact value can no longer be utilized as the standard, for there is a lower limit to the velocity that a ship will have when it contacts the pier or fender.

B. Construction

Construction methods of installing fender systems pose no special problems for the more standard types such as fender piles or gravity fenders. When using rubber or spring buffers additional care must be taken

in driving the fender piling to insure that the heads of the piles are within closer tolerances regarding their distances from the decking. The buffers can then be installed without prestressing either the buffers or the piling. Slinging gravity fenders will require fairly heavy lifting equipment so arranged that the fenders can be installed prior to placing of the decking. If the decking is placed first, then special slings will have to be used to allow the fenders to be swung off balance underneath the pier. The one fender system that will probably require most skill and care during installation is the hydraulic damper. No standard designs have as yet been devised, but the mechanisms currently used are all rather complicated, necessitating close adherence to tolerances. It is believed that the work on any fender system, except perhaps the timber fender pile tied to the deck, requires more close attention to tolerances than previously necessary in waterfront structures.

C. Restrictions to Operation

Berthing procedures are pretty much the problem of the individual ports and their authorities. Limiting restrictions must be maintained on all berths whether fenders are used or not. It has been suggested that the pilots and ship handlers will govern their berthing speeds according to the ability of the individual pier or fender system to absorb shock. If the fender system is good, then the ship will be brought alongside more smartly than if it were incapable of taking large impact loads. From a study of human psychology this idea seems to hold merit. If so, then it is necessary for the authorities to establish regulations and require adherence by the ship's personnel. Failure to do so will result in con-

tinuous damage to the piers and to the fenders with greatly increased maintenance costs.

D. Maintenance

One of the most important factors of design, so often overlooked by owners and designers alike, is the cost and problems of maintenance. This failure is not only confined to fenders and waterfront work, but to all phases of the construction profession. Those who understand and take steps to ease the maintenance problems are to be congratulated, for these are the persons who are properly considering the true cost of a particular design. It is understandable when a designer, checking construction costs of labor and material, decides to use a certain material or apparatus over another because it seems to be the cheaper. In many cases it is, but to be certain it is necessary to consider the maintenance and replacement costs and problems over the life expectancy of the object. This is especially true with fenders.

Initially timber fender piling is relatively inexpensive for the protection they give, but will they still show the same economy after five years of continuous use? As an example, if the timber fender piling initially costs one-half of the amount for material and erection as does a comparable gravity fender system, and after five years it is found that the berth has had to be closed for repairs for twenty days for repairs to the timber fenders and for ten days for the gravity fenders, there will be first an operational saving of time which is worth a certain amount of money. Next, if approximately one-third of the piles need to be replaced (which is a fair average for a period of five years in a port with moderate

traffic) and only one of the gravity fenders needsto be replaced, we find here a large difference in monetary expenditure. Add to this the equipment rental and crew wages required for these different operations and the resulting savings may be enough to swing the decision to gravity fenders rather than the fender piles. This is meant as an imaginary example, and does not indicate that such will always be actually the case.

Before maintenance costs can be used in comparison with the construction costs, on-the-site inspections and investigations must be undertaken. It can be said that in almost any harbor marine borers will be found to some degree. When considering the use of timber piles the effect of these borers must be analyzed. Standard practice is to use untreated piling for fenders, except in those designs where wearing plates of metal or rubber are used to protect the outer surface of the pile from the action of the ships. In these latter cases, treated piling is usually employed. If untreated timber is used, then the piles must be considered to be useless for their designed impact absorbing qualities after the borers have been active over a period of time that can be determined only by inspection of existing structures. Whether treated timber is used or not, if the abrasion is such that the surface wood is broken enough to allow penetration of the borers, then the timber must be considered as untreated.

In any waterfront structure where the materials are subjected to action by the sea water, cognizance of this fact is required for a proper design. In an independent study(44) the author investigated the literature on deterioration effects of sea water on concrete and steel with the

finding that the deterioration of these materials is often underestimated. This deterioration, if included in the original analysis, will give more accurate cost comparisons and will lead to the design and construction of fender systems that will give better service with less maintenance problems. The use of steel, particularly that which has many crevices or which will be alternately immersed and then air dried, will be the source of many maintenance headaches that will be difficult to overcome. Steel in sea water should be adequately protected against corrosion and should be of simple, smooth design to reduce hidden pockets of rust. A soft or poor grade of concrete will be affected by the action of sea water, particularly if subjected to alternate freezing and thawing and alternate wetting and drying. Concrete deterioration, if excessive, can cause complete failure of the fender within a very few years. Spalling of the concrete surface of a gravity fender will be a source of considerable expense in the repair or replacement of the fender. The small additional cost of a good concrete mixed with an air-entraining admixture will more than repay the designer with a greatly increased life expectancy and reduced maintenance.

In the author's search through the literature on the subject of fendering, very little information has been found regarding the ability of different types of fenders to withstand constant usage over years of service. The recording of maintenance problems was almost nil, while erection and repair procedures were practically ignored. It is the opinion of the author that no fender or fender system can be properly designed without a good background knowledge of the maintenance and operational problems inherent in the various systems. Until much more experience has been gained

with the results analyzed and published, the designer is handicapped in making an adequate selection commensurate with the interests of the owner. It is understood that the holders of the patents of the different fender systems are loath to publish any information that may be detrimental to the sales of their products, and this fact is appreciated, but to provide the best fendering possible in the future, these results must be made known.

X. NEW IDEAS FOR FENDERS

To make any study of a material or mechanism complete, it is necessary for the author to put down his ideas on how to improve the existing facilities and perhaps design, invent, or guess at some new methods of his own that he considers as good or better than those currently used. With this in mind the author has been pondering over several ideas that seem on the surface as being either too costly or presenting too many insurmountable obstacles. It is necessary to find a simple, inexpensive fender that will meet the velocity and mass sensitivity requirements; that will provide adequate absorption of kinetic energy; that will not over-stress the hull of the ship; that will allow longitudinal movement with little or no transfer of the longitudinal impact to the pier or fender; that will require little maintenance; and will be easy to repair. It is easy to condemn the efforts of others, but when the need for a new and better design is presented, then the problems faced by the other designers are fully realized.

Like so many other investigators in the field, the author knows that he has not been able to find the perfect fender, and as a matter of fact, he has not found one that he considers much better than those already in use. Several ideas and suggestions for improvement of existing fender systems have been arrived at and these will be presented in due course. Actually, there are many methods of fendering that are as good or better than those now in use, but there are drawbacks to each that are at present insurmountable. In the future it is hoped that these other principles can be applied to the field of fenders and that the results

will be much better than any we now have.

A. Pneumatic Fenders

It is considered that the use of pneumatic fenders is being overlooked. By using a central pressure tank to limit the pressures that will be applied to any individual fender, rubber bags shaped in the form of a rectangle could make excellent fenders. The surface of the fender bag would have to be of a heavy rubber reinforced with wire fabric to prevent abrasion from tearing a hole in the surface. The bag could be backed on the pier by a criss-cross of timber planks, or could be placed directly against a quay wall or bulkhead. The size of the bag would be determined by the pressure of the air and the kinetic energy of the ship. Safety valves on the air tank would protect the system from overloading. A system of self-sealing layers could be utilized to protect the bags from small leaks, and a one-way restriction or valve in the air supply line would allow the pump to maintain the pressure in the system even if one bag were torn open. The air supply could be taken care of by one small compressor used to maintain constant pressure in case of line leaks or bag punctures. The weight of such a system on the piles of the main structure would be negligible and the unit stress placed on the hull of the ship would be no greater than the air pressure. One problem that would have to be overcome would be the effect of longitudinal movement of the ship along the pier while in contact with the bag. A lubricating compound may be the answer to this. In the event that rubber is considered too expensive or difficult to use under these circumstances, then plastics could be utilized. Cost figures of plastics are relatively low when compared to other materials that are used for fenders. They can be molded

easily with strengthening ribs and internal reinforcing of steel mesh.

The bags may be ballasted with a heavier material such as sand or held down by chains or cables so that they will not float. They will be light weight so that one man or two at the most would be able to replace a unit within a few minutes, thereby tieing up the pier space for only a short time. In no case would the berth be out of service for a time anywhere close to the turn around required for the repair of any of the other fenders. Replacement bags could be held available and carried into place easily. The air connections would be hoses with threaded connections either of rubber or plastic and would be flexible and not subject to abrasion or damage.

One of the advantages of this system is that the air pressure could be varied to compensate for the size of the ship using the berth. If required, additional bags could be installed to take care of any larger ship using the berth. The system would be extremely flexible, and in the opinion of the author very inexpensive when compared to the other methods now in use. If it is argued that the fenders may only last a year or two, the author points out that the cost of replacement and repair will be minor compared to the present methods that also require replacement in some cases within a year or two. Unfortunately, these bags would have to be manufactured under special order and any additional procurement would be under the same category. Repairs would have to be accomplished by experienced personnel hired either by the yard or by a local manufacturer. If these fenders could be used in large enough quantities and enough spares were kept on hand, it would pose no problem to send them some distance for repair. That being the case the repair could be relatively inexpensive

and fairly rapid with a constant high degree of quality of workmanship.

The ramifications of this type of fender are many; instead of air pressure it is possible to use water pressure, although this would complicate the design requiring heavier bags and fastening devices. Of course, the use of water as the pressure producing medium would require that this particular type be used only in the climates where freezing would not be a problem. The control of water pressure could be maintained centrally or may be controlled at each bag by a simple raising valve that would limit the pressure to say 10 psi or whatever pressure decided by the designer. Another method using water or any other fluid would be to fill the bag only half full so that as the ship came into contact with it the water would be lifted as the bag was squeezed together. The energy absorption would be in the work required to lift the mass of fluid. It is well to remember here that the absorption capacity is the work required to lift the center of gravity of the mass through a vertical distance. If the center of gravity of the original bag was at one-fourth the height and it was at one-half the height at the end of the travel or impact, then the energy absorption of the bag would be equal to the weight of the fluid times one-fourth the height. Any additional energy that would have to be absorbed would be taken by the increase of pressure as the force of the ship tends to flatten the bag. For this pressure increase some sort of relief valve would be required to prevent excessive pressures that would rupture the bag.

It is the intention of the author in the near future to make actual tests on a prototype of the above described bag. If it proves to be acceptable in practice the design will be published in engineering literature.

Cost figures will also be estimated and production possibilities will be investigated.

B. Hydraulic Fenders

An additional field of possibility is the further development of the hydraulic damper. A great amount of work has been done by the aviation industry developing a shock absorber for landing aircraft that has proven to be excellent in its capabilities. The author sees no reason why the larger hydraulic struts from aircraft cannot now be utilized for fenders. In order to compensate for longitudinal and vertical movement, the use of aircraft type wheels with low pressure tires mounted on swivel gear and protected by a hydraulic strut between the wheel and the deck would possibly prove acceptable. Such a fender would accept the initial impact normal to the pier and would allow the vertical movement or rolling and the longitudinal movement to occur without transmitting any forces to the pier. Wheels and struts that can be used in conditions where they will be in or under sea water constantly have been developed by the aircraft industry for use on seaplanes, and with only minor changes could be utilized on piers.

Assume that an aircraft weighing 100 tons lands with a velocity normal to the earth of 5 feet per second, which is about average; the kinetic energy of the airplane then is about 5600 inch-tons. If this load is taken by four hydraulic struts and wheels the energy absorbed by any one strut and wheel will be about 1400 inch-tons. Compared with the 900 inch-tons that is the capacity of a gravity fender weighing 30 tons that has been raised a vertical distance of 30 inches, it can be seen that the

hydraulic unit with wheel could give excellent results. The cost feature of this type of design has not been investigated because of the inability of the author to find adequate sources. Even if the cost were much greater than that of a comparable fendering system the reduction in maintenance and repair costs would seem to overcome the initial differences.

Neither of the above ideas provide the ideal fender, but are only possible methods of improving the energy absorbing designs now in use. Until either new materials are devised or present ones are greatly reduced in price it will be difficult to come up with a really acceptable fender design that can be used on any type of berth for any size of ship. Many of the ideas presently in use are very acceptable, and with additional development they can be more effectively used. A large number of designers are too prone to look on all new ideas with the attitude of finding only their faults, rather than to look at each new idea with the desire to find the good points of the fender and in some way increase its effectiveness and overcome its drawbacks. If this latter attitude were used by all designers it would be only a matter of time before a really good, generally acceptable fender for all installations would be devised.

Much can be done to improve existing fenders and to increase the present fund of knowledge about the amount of impact, the approach velocities of the ships, the loss of kinetic energy due to the drag effect of the water, and the amount of impact energy that can be actually taken by the hull of the vessel. Several European engineers are currently working on these problems, and have shown some interesting results. The Permanent International Association of Navigational Congresses has sponsored much

research and study of this question with gratifying interest on the part of the members. As far as can be seen or learned by the author, little research has been accomplished in this country on fender design except to utilize the results of the European engineers. It is hoped that in the future the interest of Americans will increase and that progress will be rapidly made. Designers such as Mr. Virgil Blancato, Structural Engineer with the U. S. Navy at New York, have completed designs for fenders, which although acceptable have not yet reached the design stage of the ideal fender system. These engineers are to be commended for their work.

X. CONCLUSIONS

The statement "the old medicines are the best" can in some ways fit the question of fender design, for some of the old fender systems are still the best for certain installations. The use of the timber fender pile is considered the most adequate for some piers, and indeed is considered by some engineers as being better than any other that has been so far developed. The use of hardwoods for fenders has shown very good results for energy absorption and has indicated that the over-all cost of construction and maintenance may make them the most economical. Even branches or faggots wrapped into a cylindrical shape and hung along the side of a quay have proven to be passable fenders when more suitable materials and designs are lacking. In the desire for new ideas the designer should not overlook the old for they may prove to be more acceptable than the modern innovations.

In 1953 the Permanent International Association of Navigational Congresses published the following in their Bulletin:

"....

2. We must recognize the practical nature of the use of simple fenders made of timber, faggots, old tyres and similar objects for protecting masonry quays. As regards faggots, when they are of large dimensions the kinetic energy which they are capable of absorbing is considerable; and their cost is comparatively low and there is no difficulty in replacing them. As regards timber fenders--either piles or beams--it appears advisable to use hardwoods, such as oak, azobe, or greenheart when there is any reasonable economy for constructional and maintenance costs

as a whole. Again, it is advisable--to improve the capacity of absorbing energy, both longitudinally and perpendicularly to the quay--to add rubber blocks or pads to the timber protection. .....

3. As regards mechanical shock absorbers, their use should be advised for technical and economic reasons for openwork structures....."

Let us consider once again the requirements of an ideal fender:

1) a simple mechanism, yet of strong, rigid construction
2) inexpensive and easy to maintain
3) capable of absorbing all of the kinetic energy of the berthing ship
4) does not cause excessive pressures or loads on the hull of the ship
5) it should be velocity sensitive
6) it should be mass sensitive
7) the rate of energy absorption should increase with deflection
8) it should give way to longitudinal forces
9) must act at any state of the tide
10) capable of absorbing the energy of any size ship that may moor against it
11) long life

Each of the fender systems that have been discussed have met at least several of these requirements, but none of them have been able to perform as the ideal fender. The author thinks that such a fender may be designed and it is hoped that in the near future such a fender will be developed. The fender suggested using the rubber or plastic bag under air

pressure will answer most of the requirements, but there are questions regarding several features that will have to be resolved by actual experiment.

Of the presently used fender systems, the gravity fenders and the fender piles of timber protected by a metal wearing strip and backed at the deck level with a shear sandwich of rubber are believed to be the most satisfactory for general usage. The other fender systems employing springs, hydraulic dampers, compressed air, or cork and rope are suitable for some installations but they are of a specialized nature and not for general usage. In the future, after additional development, they may be more suitable.

The question of the use of large dolphins or rotating suspended fenders is a matter that must be answered by the designer for each individual location. Insufficient information has been published regarding the actual performance of the Bell Fender to warrant the author committing himself other than to suggest that the initial cost may be excessive when compared with standard type dolphins. It should be remembered though that the Bell Dolphin is utilized for extremely heavy impacts in exposed areas where standard dolphins may not be satisfactory.

Gravity or suspended fenders have shown very good results so far and from a study of the possibilities of this type, it seems that they can be depended upon to provide good energy absorption at relatively low costs for both construction and maintenance.

Of interest is the use of rubber. It has been utilized in several different shapes and forms and it is easy to visualize many more. Its

characteristics are such that it can absorb the kinetic energy of the ship by deformation in compression, shear, or torsion. Rubber is fairly inexpensive, requires little maintenance, and can be obtained readily without undue trouble or time loss.

Hydraulic dampers are still relatively new but show excellent possibilities for future development. The problems inherent in using the hydraulic buffer for fenders have been solved to a great extent by the aircraft industry, and with proper liaison, these solutions should be made available to the marine structural designer.

The use of compressed air has not been adequately studied as yet, and in this field there seems to be a possibility of considerable advancement in fender design. The few devices currently used are rather elementary and not very efficient.

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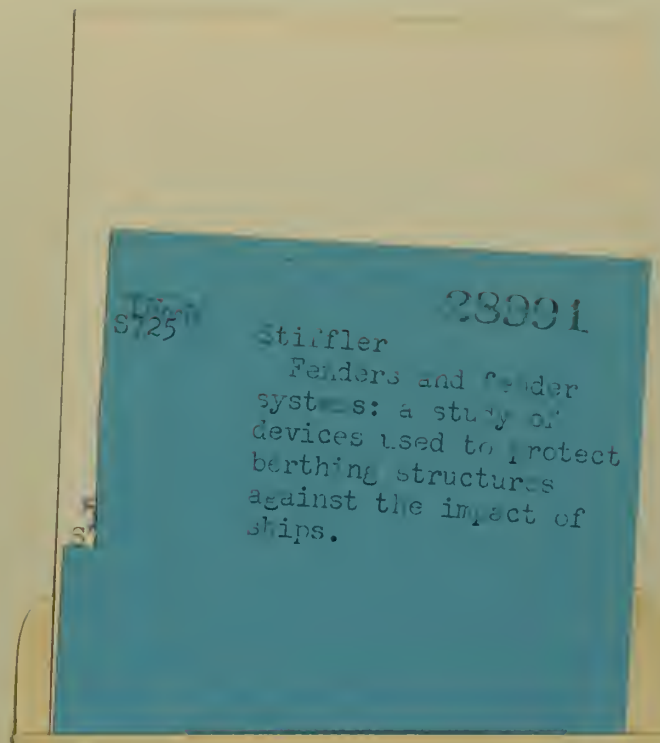
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